Young adults with acquired brain injury show longitudinal improvements in cognition after intensive cognitive rehabilitation

Young Adults with Acquired Brain Injury Show Longitudinal Improvements in Cognition After Intensive Cognitive Rehabilitation

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Abstract

Purpose

To assess the effect of an intensive cognitive and communication rehabilitation (ICCR) program on language and other cognitive performance in young adults with acquired brain injury (ABI).

Method

Thirty young adults with chronic ABI participated in this study. Treatment participants (n = 22) attended ICCR six hours/day, four days/week for at least one twelve-week semester. Deferred treatment/usual care control participants (n = 14) were evaluated before and after at least one twelve-week semester. Pre- and post-semester standardized cognitive assessment items were assigned to subdomains. Between- and within-group generalized linear mixed effects models assessed the effect of timepoint on overall item accuracy and differences by item subdomain. Subdomain analyses were adjusted for multiple comparisons.

Results

Between-group analyses revealed that treatment participants improved significantly faster over time than deferred treatment/usual care participants in overall item accuracy and specifically on items in the verbal expression subdomain. Investigating the three-way interaction between timepoint, group, and etiology revealed that the overall effects of the treatment were similar for individuals with non-traumatic and traumatic brain injury. The treatment group showed an overall effect of treatment and significant gains over time in the verbal expression, written expression, memory, and problem solving subdomains. The control group did not significantly improve over time on overall item accuracy and showed significant subdomain-level gains in auditory comprehension, which did not survive correction.

Conclusions

Sustaining an ABI in young adulthood can significantly disrupt key developmental milestones, like attending college and launching a career. The present study provides strong evidence that integrating impairment-based retraining of language and other cognitive skills with “real-world” application in academically-focused activities promotes gains in underlying cognitive processes that are important for academic success as measured by standardized assessment items. These findings may prompt a revision to the current continuum of rehabilitative care for young adults with ABI.

Keywords

Brain Injuries, Stroke, Rehabilitation, Cognition Disorders, Language Disorders

Introduction

Acquired Brain Injury

Acquired brain injury (ABI) encompasses a variety of etiologies, including traumatic brain injury (TBI), stroke, tumor, anoxic/hypoxic injury, and encephalitis among others. While sustaining an ABI at any age can have significant consequences, sustaining an ABI in young adulthood can significantly derail the trajectory of an individual's academic, career, and social development (Committee on Improving the Health and Well-Being of Young Adults et al., 2015). Unfortunately, young adults are one of the most frequently affected groups to sustain TBI (i.e., ages 15-24; Taylor, 2017) and non-fatal opioid overdose, which can lead to anoxic/hypoxic injuries (i.e., age ranges between 15 and 34, *Non-Fatal Opioid Overdose and Associated Health Outcomes*, 2019; Vivolo-Kantor, 2020). Further, the rate of stroke in college- and working-age individuals (i.e., 18-50 years) has been on the rise over the past several decades (Benjamin et al., 2019) due to an increase in vascular risk factors in this group (e.g., hypertension, diabetes; Singhal et al., 2013). Concern over the growing number of young adults with ABI in need of rehabilitation services to get their lives back on track is underscored by the fact that the majority of cognitive rehabilitation programs (i.e., approaches that target attention, visuospatial functioning, language and communication skills, memory, executive function; Cicerone et al., 2019) do not provide services at the frequency and intensity necessary to prepare them for college (e.g., Babbitt et al., 2016; Kennedy & Krause, 2011; Klonoff et al., 2006; Todis & Glang, 2008).

ABI impacts cognitive processes

ABI often leads to long-term deficits in a range of cognitive domains, such as language, attention, memory, executive function, and visuospatial/constructional processes. As cognitive processes are supported by large scale brain networks (Kljajevic, 2014; Petersen & Sporns, 2015), there is considerable overlap in impaired cognitive processes across ABI etiologies, despite differences in the nature of the injury (e.g., focal vs. diffuse). Aphasia is common after focal injury, such as left hemisphere stroke, but it has also been demonstrated after TBI (Kiran, 2012; McAllister, 2011; Norman et al., 2013), especially more moderate to severe cases. Attention, memory, and executive function are consistently impaired after diffuse injury (i.e., TBI; McAllister, 2011; Rabinowitz & Levin, 2014; anoxic/hypoxic injury; Cullen & Weisz, 2011; Shah et al., 2004), but can also occur after focal injury, for example, in the context of stroke-induced aphasia (Gilmore, Meier, et al., 2019; Kertesz & McCabe, 1975; Lang & Quitz, 2012; Purdy, 2002; Seniów et al., 2009; Simic et al., 2017; Villard & Kiran, 2015). Visuospatial/constructional deficits occur across ABI etiologies (Arciniegas & Anderson, 2004; Cullen & Weisz, 2011; Gehring et al., 2010; Hokkanen et al., 1996; McKay et al., 2008; McKenna et al., 2006; Shah et al., 2004; Tonning Olsson et al., 2014) with some variation in the frequency or severity based on location of injury (Wilde, 2006, 2010). In sum, individuals with ABI have overlapping patterns of cognitive deficits in language, attention, memory, executive function, and visuospatial/constructional processes, which are important for academic success.

Cognitive processes important for college

The same cognitive processes (i.e., language, attention, memory, executive function, visuospatial/constructional) that are frequently impaired in ABI are often relied

upon by young adults in college. There is a great deal of research emphasizing the importance of various cognitive domains on college performance with a general pattern of higher performance in the cognitive domain of interest accompanying higher academic achievement. For example, neurotypical college students attained higher grades (Weyandt et al., 2013) and were at lower risk for academic challenges (Weyandt et al., 2017) than college students with attentional impairments. College freshmen with higher working memory performance had higher grade point averages (GPAs; Hannon, 2014), a standard metric of academic achievement, than students with lower working memory performance. In terms of executive function, studies have shown that students with greater conceptual reasoning ability (Rohde & Thompson, 2007), study skills (Hartwig & Dunlosky, 2012; Hassanbeigi et al., 2011), strategy usage (Taraban et al., 2000), self-regulation (Cohen, 2012), and self-efficacy (Krumrei-Mancuso et al., 2013) earned higher GPAs than their counterparts. As expected, positive relationships have also been found between visuospatial processing ability and performance in science (Castro-Alonso & Uttal, 2019) and math (Rohde & Thompson, 2007). Finally, the reliance on language skills in college is unarguable (Hargie, 2006; Mahmud, 2014; Morreale & Pearson, 2008; Rubin & Graham, 1988). For example, students with better listening performance (Feyten, 1991) and reading comprehension (Royer et al. 2016) had greater success in college than their counterparts with worse performance in those domains.

Based on the pathophysiology of ABI, it is not surprising that young individuals with ABI struggle with academics after their injury. Students with TBI report that deficits in attention, executive function, and memory function impact their academic performance (Kennedy et al., 2008). This group also endorses having to review material to a greater

extent than pre-injury and having difficulty understanding course material (Cahill et al., 2014). Some students with TBI modified their academic status by taking fewer courses per semester than before their injury, and even changed their career goals (Kennedy et al., 2008; Todis & Glang, 2008). Predictably, young adults with disability (including TBI) graduated from post-secondary education less often than peers without disability (Sanford et al., 2011). Over 40% of young adults with stroke demonstrate long-term language and other cognitive impairments, which can impede return to work and school (Yahya et al., 2020). Unfortunately, the impact of stroke on academic advancement for young adults with ABI has been under-studied relative to TBI and not surprisingly, services for this unique group are often inadequate and disjointed (Radford & Walker, 2008). One study investigating the academic experiences of young adults with stroke-induced aphasia revealed self-endorsed difficulty taking notes, recalling what the professor said, and remembering what they had read (Mattuzzi & Pfenninger, 2018). Study participants also ranked class activities involving speaking (e.g., oral presentations) as the most stressful and reported feeling anxious about their language difficulty in class. While individuals with TBI and stroke-induced aphasia may experience difficulty with the same academic activities (e.g., recalling information from the lecture), in many cases, this difficulty is driven by different underlying deficits that should be considered when targeting these activities in therapy (e.g., individuals with aphasia may not be able “to recall information” because of auditory comprehension impairments that affected encoding or lexico-semantic impairments that affected access and retrieval; individuals with TBI may not be able “to recall information” because of attention impairments that affected encoding or memory impairments that affected retrieval).

Individuals with tumor and encephalitis also experience academic challenges after injury. Parsons et al. (2012) report that over half of young adult cancer survivors (i.e., first cancer diagnosis between 15 and 29 years of age) endorsed challenges with return to work or school that were cognitive in nature (e.g., “trouble keeping up with work or studies”, “forgetting things”, “hard to pay attention at work or school”). Young adults with encephalitis also experience academic challenges post-injury and may need specific strategies to succeed (Obrecht & Patrick, 2002). In fact, Fraas & Bellerose (2010) investigated the effects of a mentoring program for a young adult with encephalitis who experienced difficulty adjusting to school post-injury due to persistent memory impairment, emotional deficits, and fatigue. In sum, young adults sustain ABI when they are on the precipice of launching their educational and career goals. Associated language and other cognitive impairments can substantially disrupt their academic and vocational trajectories. Thus, it is paramount that this unique population receives cognitive rehabilitation that is specifically tailored to their personal goals, such as getting back on track toward postsecondary education and a future career, and clinical deficit profiles (e.g., aphasia, executive dysfunction).

Current cognitive rehabilitation approaches

Many young adults with ABI receive cognitive rehabilitation to address deficits in the domains discussed in the preceding sections. Cognitive rehabilitation can take several forms, including restorative, compensatory, comprehensive, and/or contextualized approaches (Cicerone et al., 2019; Hart, 2010; Institute of Medicine, 2011; Wilson, 1997, 2002; Ylvisaker et al., 2002). It can also be modular, targeting a cognitive domain (i.e., attention, visuospatial functioning, language and communication skills, memory,

executive function; Cicerone et al. 2019) in isolation (e.g., Sohlberg et al., 2000), or be multimodal, targeting multiple cognitive domains simultaneously (e.g., Cicerone, 2008).

Despite the availability and application of cognitive rehabilitation approaches, there is no clear evidence that existing programs substantially contribute to the advancement of young adults with ABI to college. Comprehensive rehabilitation programs report positive functional outcomes (i.e., productivity, independence; Cicerone et al., 2000, 2005, 2011). Yet, the frequency of return to school (Klonoff et al., 2006; Sarajuuri et al., 2005) is difficult to discern as it is often combined with return to work (Cicerone et al., 2004, 2008; Goranson et al., 2003; Vanderploeg et al., 2008) or not reported (Cooper et al., 2017; Mills et al., 2006; Schönberger et al., 2006; Svendsen & Teasdale, 2006). Additionally, one rehabilitation program, designed to support young adults with ABI by providing coaching support for studying and learning, time management, and interpersonal interaction, reported modest post-program benefits for the two individuals included in the study (Kennedy & Krause, 2011). Yet, the Kennedy & Krause (2011) program was designed for young adults who have already been admitted into college and thus, does not serve those with more moderate to severe impairments that may require intensive, academically-focused rehabilitation to advance to college.

Our own prior work in this area has demonstrated the feasibility of implementing an intensive, academically-focused cognitive rehabilitation program specifically for young adults with ABI who wish to pursue college, but currently cannot due to the severity of their language and/or other cognitive deficits. The Intensive Cognitive and Communication Rehabilitation (ICCR) program includes classroom-style lectures, individual therapy, and technology training for six hours/day, four days/week, and12-week

iterations. A central tenet of the program is that the integration of impairment-based retraining of language and other cognitive skills with "real-world" application in academically-focused activities (e.g., listening to a lecture and taking notes, studying for quizzes, answering discussion questions) should drive change in underlying cognitive processes as measured by standardized assessment items (Meier et al., 2017)— an alternative approach to interventions that target impairment and measure change in function (e.g., Cantor et al., 2014; Doesborgh, 2003). Full details of the initial efficacy study are reported elsewhere (Gilmore, Ross, et al., 2019), and thus, the results will only be summarized here. Six young adults with chronic ABI were enrolled in the study (n = 4 treatment participants, n = 2 control participants). Before and after each treatment/no-treatment period, all participants underwent a battery of standardized assessments examining global cognitive function. Treatment participants showed statistically significant gains in at least one standardized assessment of cognitive function, while control participants did not, suggesting that the improvements achieved by the treatment participants were likely attributable to the intervention.

Summary of the problem

Young adults rely on executive function, attention, memory, visuospatial processing and language domains to succeed in college. These domains are often impaired in young adults with chronic ABI and cognitive deficit profiles overlap across ABI etiologies. Treatment approaches are commonly segregated by ABI etiology, despite obvious benefits to including individuals with different ABI etiologies in the same intervention (e.g., provision of a peer rehabilitation group, balance of impaired and spared processes in a group context that may facilitate collaboration and empowerment).

Cognitive rehabilitation programs for young adults with ABI struggling to advance to college should focus on impaired cognitive domains that have been shown to support academic success in healthy young adults. Nevertheless, academic outcomes for existing cognitive rehabilitation programs are limited in the literature. Further, cognitive function is not consistently or thoroughly assessed as an outcome measure for such programs (e.g., Cooper et al., 2017; Svendsen & Teasdale, 2006). Some studies have reported an aggregate score (e.g., Cicerone et al., 2004, 2008), but these types of composite or summary scores derived from commonly-used standardized outcome measures (e.g., WAB-AQ, RBANS-Total) are coarse and may obscure treatment-related gains in specific cognitive domains targeted by an intervention. While subtest scores can be inspected as an alternative, this approach can also be flawed. The analysis in the present study leveraged rich item-level from four commonly-administered standardized assessments of cognitive function to overcome some of these challenges and capture subtle improvements in specific cognitive domains.

The present study investigated the effect of the ICCR program, which combined targeted retraining of language and other cognitive skills with repeated opportunities for application in a functional context (i.e., classroom-based activities), on a range of underlying cognitive domains as measured via standardized assessment battery items in a group of young adults with ABI pursuing post-injury college enrollment. This overall study objective was addressed via the following specific aims:

1) comparing overall cognitive function and performance on specific language and other cognitive domains—known to be impaired in individuals with ABI, important for academic success, and the focus of this multi-faceted integrated

intervention—over time between a group of young adults with ABI who participated in ICCR (i.e., treatment) and a group of young adults with ABI who did not (i.e., deferred treatment/usual care control)

2) examining longitudinal performance in overall cognitive function and specific language and other cognitive domains for the treatment and control groups individually

3) assessing whether changes in overall cognitive function for the treatment versus control group over time differed for young adults with traumatic versus non-traumatic ABI etiologies.

Methods

Study Design

The study employed a longitudinal non-randomized intervention design (Moerbeek, 2008; Sedgwick, 2017). Participants who met the eligibility criteria were given the choice to enroll in the treatment or defer for a semester. If they chose to defer treatment, they were given the standardized assessment battery (see Assessment section). Before the start of the next semester, the study team contacted them to complete the assessment battery again and they were again given the option to enroll in the intervention (as participation in multiple semesters was permitted) or continue to defer. The deferred treatment control phase always preceded the treatment phase. While in the deferred treatment/usual care group, participants were asked to refrain from taking college courses, but otherwise were able to participate in their daily lives (e.g., volunteer, work, attend outpatient therapy). Participants who did not attend outpatient speech therapy in the community during the control phase were considered “deferred treatment”

controls and those who sought outpatient speech therapy in the community of their own accord during the control phase were considered “usual care” controls. See Supplemental Section 1 for details about the deferred treatment/usual care control participants’ activities during the study.

Recruitment

Participants were recruited from the greater Boston area and nationally for this longitudinal study via the following methods: 1) word-of-mouth; 2) referrals from speech-language pathologists, neuropsychologists, and physicians; 3) posting on professional message boards; 4) social media; and 5) conference presentations. Primary eligibility criteria for this study’s enrollment included: 1) young adult between the ages of 18 and 40 (Erikson, 1997; McLeod, 2018); 2) sustained an ABI; 3) presence of language and/or other cognitive deficits as determined by performance below normal limits on the Western Aphasia Battery-Revised Aphasia Quotient (WAB-R AQ; Kertesz, 2006; < 93.8) and/or the Repeatable Battery for the Assessment of Neuropsychological Status Total Index Score (RBANS; Randolph, 2012; < 85); 4) goal of enrolling in and/or returning to post-secondary education; and 5) adequate hearing for conversation and adequate vision for functional reading based on medical records review, self/caregiver report and/or clinical judgment. Potential participants with concomitant neurological disease (e.g., epilepsy, attention deficit disorder) were considered for inclusion on an individual basis. Individuals with neurodegenerative disease were excluded.

Participants

Between Fall 2016 and Fall 2020, thirty-seven individuals were screened for the study. Seven individuals were excluded (i.e., five individuals did not meet inclusion

criteria, two individuals declined to pursue the program after screening). The remaining thirty participants were enrolled in the present study.

Sixteen unique young adults enrolled into the treatment group immediately. Fourteen unique young adults (8 males, age mean (SD): 25.99 (5.64) years, months post onset M (SD): 57.77 (46.27) months, TBI = 7, Non-TBI = 7; WAB-AQ M (SD): 84.15 (15.73), Range: 43.7 – 99.5; RBANS-Total M (SD): 57.93 (10.37), Range: 45 - 79) enrolled as deferred treatment/usual care control participants. Six of these fourteen deferred treatment/usual care participants (P13/C7, P14/C10, P17/C12, P18/C2, P19/C13, P22/C11) transitioned to the treatment group after completing their control study phase(s), increasing the treatment group to twenty-two young adults (15 males, age mean (SD): 24.24 (4.43) years, months post onset M (SD): 52.00 (39.10), TBI = 10, Non-TBI = 12, WAB-AQ M (SD): 78.78 (20.93), Range: 18.8 – 99.6; RBANS M(SD): 55.09 (10.84), Range: 44 – 78). See Figure 1 for flow chart of recruitment, enrollment, self-allocation to groups, and analysis. See Model Building and Structure section for how the six participants who contributed data to both groups were managed in the analyses.

All participants provided written consent to participate in the study in line with human subjects policies and procedures put forth by the Boston University Institutional Review Board. They each had attained at least a high school education by study enrollment, although a high school degree was not required for inclusion. The treatment and deferred treatment/usual care control groups did not significantly differ on age, months post onset, WAB-R AQ, RBANS Total, or education level, based on Welch's two-sample t-tests ($p > .05$ level). See Table 1 for additional demographic details, including

any premorbid history of mental health conditions or learning disabilities/differences endorsed during screening.

Assessment

All participants were administered a standardized assessment battery before and after each semester of the intervention. For participants who participated in multiple, consecutive semesters of the study, the post-treatment data from the previous semester was used as the pre-treatment data for the subsequent semester. The following tests were selected from a larger battery of assessments administered as part of the intervention protocol: 1) the WAB-R to measure language function (e.g., verbal expression); 2) the RBANS to evaluate other cognitive function (e.g., memory); 3) the Scales of Cognitive and Communicative Ability for Neurorehabilitation (SCCAN; Holland & Milman, 2012) to assess language and other cognitive functions (e.g., attention, reading); and 4) the Discourse Comprehension Test (DCT; Brookshire & Nicholas, 1993) to evaluate narrative-level language function (i.e. auditory and reading comprehension at the multi-paragraph level). See Supplemental Section 2 for pre-treatment/deferred treatment subtest scores for the WAB-R, RBANS, SCCAN, and DCT for all participants (i.e., collected at the start of their first timepoint in the study).

Behavioral Intervention

ICCR involved classroom-style lectures; group and individual therapy; and computer- and application-based training (Gilmore, Ross, et al., 2019). Participants attended ICCR six hours/day, four days/week for at least one 12-week semester (i.e., approximately 240 hours/semester). As demonstrated in Figure 2 and detailed in Table 2, participants were exposed to material from four different college-level courses per

semester, alternating between two sets of courses daily (e.g., Monday/Thursday: Psychology & Statistics; Tuesday/Friday: Advanced Biology & English Literature). Daily treatment components included: 1) watching a pre-recorded lecture as a group (e.g., taxing attention, auditory comprehension); 2) reviewing lecture content as a group (e.g., targeting short-term memory, verbal expression, auditory comprehension, problem solving); 3) answering practice quiz questions about the lecture as a group (e.g., recruiting short-term memory, problem solving, reading); 4) participating in a discussion- or project-based course as a group (e.g., taxing verbal expression, reading, writing, problem solving); 5) completing individualized technology training in a group context (e.g., focusing on various cognitive domains based on participants' clinical profile and needs); and 6) engaging in individual therapy with a speech-language pathologist (e.g., targeting various cognitive domains based on participants' clinical profiles and interests). Participants were able to take breaks as needed throughout the sessions. If they missed a session, they were provided instructions to access the material at home and/or during technology time on the next program day and any missed quizzes were made up. Of note, average attendance was 93%, suggesting good adherence to the treatment intensity and acceptability for participants.

As detailed in Table 2, the majority of the intervention was group-based and was delivered in a college classroom by the speech-language pathologist responsible for the classroom-based intervention and trained study support staff (i.e., graduate students in Speech, Language, and Hearing Sciences and/or research assistants from the Aphasia Research Laboratory). Courses were developed using open source academic content, such as Khan Academy (*Khan Academy*, 2017) and Open Yale (Bloom, 2012). Trained

study staff developed lecture notes and quiz questions independently and/or adapted from materials provided by the course's source. All new speech-language pathologists, graduate student clinicians, and research assistants were trained via a combination of in-person and hands-on experiences as well as review of written protocols before implementing the intervention procedures.

Individualized speech-language therapy was provided by a graduate student or clinical fellow in speech language pathology under the supervision of a licensed and certified speech-language pathologist. For each individual, therapy goals were established and targeted within weekly one-on-one treatment sessions. Treatment goals were generated via review of standardized assessment results, observation of client performance within the group setting, and collaboration with clients and/or their families to meet specific needs with respect to language and other cognitive domains. Individual treatment activities incorporated evidence-based cognitive rehabilitation approaches (Cicerone et al., 2019), such as semantic feature analysis (Gilmore et al., 2018), metacognitive strategy training (Kennedy et al., 2008), and copy and recall treatment (Beeson & Egnor, 2006).

One of the primary thrusts of the ICCR program is the benefit of "real-world" application and thus, the ICCR program was delivered in a classroom setting (i.e., the same rooms used by Boston University students). Treatment participants' experiences were similar to those of students taking courses in typical college classrooms in several ways. For example, participants had to follow a schedule, including preparation for lunch. They traveled to different rooms for classes at times and for individual therapy. They also were responsible for remembering to bring school supplies and letting the clinician know

366 if they would be out or had to leave early. The morning courses were generally cumulative
367 in nature with each session's lecture content building on previous course material as is
368 common in college. Participants watched course lectures as a group and took turns
369 answering questions or explaining concepts to their peers. Similar to a "real-world" college
370 course, participants inadvertently distracted one another during class (e.g., searched
371 through their bookbag for a pen, got up to use the restroom).

372 ***Operations during the COVID-19 Pandemic***

373 The program transitioned to remote delivery via Zoom during the Spring 2020
374 semester and continued as such through Fall 2020. There was no interruption of care in
375 Spring 2020 as the program transitioned during a natural break in the semester. The roles
376 of the speech-language pathologists responsible for classroom- and individually-based
377 treatment did not change, nor did those of the study staff trained to support these program
378 components. The classroom speech-language pathologist lead the pre-recorded lecture
379 viewing, the lecture review sessions, and the seminar course discussion via Zoom with
380 "push-in" support from the graduate student clinicians. The individual therapy was also
381 provided over Zoom with "real-time" feedback and support from the supervising speech-
382 language pathologist. Finally, delivering ICCR remotely during the COVID-19 pandemic
383 simulated the experiences of college students across the globe who also transitioned to
384 online courses in accordance with safety guidelines. While potential advantages (e.g.,
385 access to services outside of greater Boston area) and disadvantages (e.g., group
386 dynamic changes) of remote ICCR delivery must be acknowledged and formally
387 investigated in future work, extensive efforts were made to maintain the protocol delivery

across in-person and remote means as detailed above, and thus, data from remote ICCR were included in the analyses.

Data Analysis

As shown in Figure 3, items from the WAB-R, RBANS, SCCAN, and DCT were assigned to one of ten subdomains based on how they were classified in the parent standardized assessment (i.e., auditory comprehension, reading comprehension, verbal expression, written expression, attention, memory, problem solving, orientation, upper limb/facial/instrumental apraxia, visuospatial/constructional). This method worked well for the majority of the items, except when an item's subtest name did not clearly match one of the ten subdomains. In those cases, items were assigned to the subdomain that reflected the primary nature of the item, based on neuropsychological reference materials (Lezak et al., 2012) and clinical judgment. The reader is referred to Supplemental Section 3 for additional detail regarding the management of these items. Item accuracy was represented by a pair of columns in the analyses: 1) the number of points scored on an item; and 2) the number of points missed on an item to capture the binary scoring system in which each point was either scored or missed by the participant.

Growth curves

A growth curve analysis approach was implemented to accomplish this study's specific aims for several reasons (Curran et al., 2010; Oleson et al., 2019). First, it captures longitudinal performance for the overall group, while accounting for differences in baseline performance and change over time between participants, an important consideration given the known variability in recovery and treatment response in this population (Forkel et al., 2014; Lazar et al., 2008; Lazar & Antoniello, 2008; Millis et al.,

2001). Second, it can predict outcomes given multiple repeated measurements for participants and third, it can manage missing data or unequal sample sizes over time — valuable advantages given this study's longitudinal design.

Model building and structure

Data were analyzed using generalized linear mixed effects models (GLMM), an extension of logistic regression that includes fixed and random effects and a common approach to growth curve analysis. In keeping with the recommendation to build a maximally complex random effects structure that is theoretically-supported by the dataset and research question (Barr et al., 2013), a GLMM was constructed to predict overall item accuracy with timepoint, group, and their interaction as fixed effects and etiology as a categorical covariate. Random effects included random intercepts for participant and item, and by-participant random slopes of timepoint and group. The by-participant random slope of group was included to allow for differences in the slope for the deferred treatment/usual care and treatment phase for the six participants who contributed data to both groups. The full random effects model (i.e., with random slopes of timepoint and group) produced a singular fit, and so did a model without covariances between random slopes for group and the other by-participant random effects, suggesting that the random effects structure was overly complex for the dataset. Thus, in keeping with best practice in mixed effects modeling (Brauer & Curtin, 2018; Meteyard & Davies, 2020), the random slope of group was removed and a model with random intercepts for participant and item and by-participant random slopes for timepoint was fit with the same fixed effects structure. The model syntax for the between-group (BG) GLMMs were subsequently constructed as follows:

BG1) Overall effect of timepoint by group model:

cbind(points scored, points missed) ~ timepoint * group + etiology + (timepoint | participant) + (1 | item)

BG2) Effect of timepoint by subdomain and group model (intermediate model with two-way interaction):

cbind(points scored, points missed) ~ timepoint * (subdomain+group) + etiology + (timepoint | participant) +(1 | item)

BG3) Effect of timepoint by subdomain by group model (three-way interaction):

cbind(points scored, points missed) ~ timepoint * subdomain * group + etiology + (timepoint | participant) +(1 | item)

Within-group (WG) GLMMs were conducted separately for the treatment and deferred treatment/usual care groups with similar syntax (i.e. removed interaction term between group and the other predictor variables):

WG1) Overall effect of timepoint model:

cbind(points scored, points missed) ~ timepoint + etiology + (timepoint | participant) +(1 | item)

WG2) Effect of timepoint accounting for subdomain model (intermediate model with intercepts for subdomain):

cbind(points scored, points missed) ~ timepoint + subdomain + etiology + (timepoint | participant) +(1 | item)

WG3) Effect of timepoint by subdomain model (intercepts and slopes for subdomain):

456 cbind(points scored, points missed) ~ timepoint * subdomain + etiology + (timepoint
457 | participant) + (1 | item)

458 These model structures allowed for testing the effects of interest. In BG1, the
459 timepoint-by-group interaction term captured group differences in the effect of time on
460 performance; that is, the effect of treatment (relative to control) on rate of improvement.
461 BG2 includes effects of subdomain and a timepoint-by-subdomain interaction term to
462 model differences between subdomains, thus providing the comparison point for BG3,
463 which also includes the three-way timepoint-by-subdomain-by-group interaction to model
464 subdomain differences in the effect of treatment (group differences in rate of change).
465 Nested model fit was compared using likelihood ratio tests (implemented with the anova
466 function in R). A statistically significant improvement in model fit for BG3 compared to
467 BG2 would indicate that the subdomains differentially responded to treatment, which can
468 be further evaluated by estimating domain-specific intercepts and slopes from the
469 between group subdomain model (BG3).

470 For within-group models, the timepoint effect in WG1 captures the rate of change
471 over time for that group. WG2 includes overall accuracy differences between subdomains
472 and WG3 includes differences between subdomain in rate of change (timepoint-by-
473 subdomain interaction). As for the between-group models, nested model fit comparisons
474 based on likelihood ratio tests (implemented with the anova function in R) were used to
475 evaluate whether that interaction term in WG3 statistically significantly improved model fit
476 compared to WG2. If it did, subdomain differences were further evaluated by estimating
477 domain-specific intercepts and slopes from the within-group subdomain model (WG3).

In each model, item accuracy served as the dependent variable. One stipulation of a logistic mixed effects regression model is that the outcome variable is expressed in integers. Standard scoring for six items of the WAB-R use half-points (i.e., five items from the dictated letters subtest were given a score of 0.5 or 0; the alphabet and numbers item: each letter or number correctly written was scored with 0.5 for a total score of 22.5 points), so these scores were scaled up by a factor of two. Otherwise, traditional rounding rules were applied to all other decimal values in the points scored column (i.e., greater than or equal to 0.5 round up to the nearest integer; less than 0.5 round down to the nearest integer).

All of the models included ABI etiology as a dummy-coded categorical covariate with two levels (i.e., TBI, non-TBI), random intercepts for participant and item to allow for differences in starting accuracy across participants and items, and by-participant random slopes for timepoint to model individual differences in rate of accuracy change over time. Timepoint was coded as a numeric predictor (i.e., Pre-timepoint= “0”, Post-1 timepoint = “1”, Post-2 timepoint = “2”, Post-3 timepoint = “3). As depicted in Figure 1, 22 participants contributed data to the Pre- and Post-1 treatment timepoint, 15 went on to complete another semester of treatment, contributing data to the Post-2 treatment timepoint, and 13 went on to complete another semester of treatment, contributing data to the Post-3 treatment timepoint. 14 deferred treatment control participants completed one semester as a control, contributing data to the Pre- and Post-1 control timepoint and 5 went on to complete a second semester as a control, contributing data to the Post-2 control timepoint (n = 5). GLMMs are robust to unequal sample sizes, which limited concern about the differences in sample size between the treatment and deferred treatment/usual care

groups (Curran et al., 2010; Oleson et al., 2019). Furthermore, only timepoints that included at least five participants data were analyzed to minimize bias of the fixed effects estimates that were of primary interest (i.e., timepoint, group; Brysbaert & Stevens, 2018; Heagerty & Kurland, 2001; Maas & Hox, 2005). Group was dummy-coded as a categorical variable with two levels (i.e., controls, treatment) with deferred treatment/usual care controls as the reference level. Subdomain was dummy-coded as a categorical predictor variable with ten levels (i.e., auditory comprehension, verbal expression, written expression, reading comprehension, attention, memory, visuospatial/constructional, upper limb/facial/instrumental apraxia, orientation, and problem solving) with attention as the reference level.

To increase interpretability, log-odds estimates from the GLMMs were transformed to predicted probability in the plots and both log-odds and predicted probability were reported in the tables (Heiss, 2020; Sauer, 2017). Both original and Benjamini-Hochberg (BH) adjusted p-values were reported for domain-specific slope estimates for the timepoint-by-subdomain-by-group (between-group GLMM) and timepoint-by-subdomain analyses (within-group GLMMs for treatment and deferred treatment/usual care control groups individually). Data management, visualization, and statistical analyses were completed in R (R Core Team, 2020) with the support of the following packages: lme4 (v1.1.26; Bates et al., 2015), lmertest (v3.1.3; Kuznetsova et al., 2017), tidyverse (v1.3.0; Wickham et al., 2019), broom (v0.7.6; Robinson & Hayes, 2020), patchwork (v1.1.1; Pedersen, 2020), and multcomp (v1.4.16; Hothorn et al., 2008).

Results

Between-group analyses

Overall effect of timepoint by group

As reported in Table 3 and demonstrated in Figure 4, participants in the treatment group demonstrated significantly lower overall item accuracy than the deferred treatment/usual care control group at baseline (B(SE) = 0.19 (0.04), Predicted Probability (Pred. Prob.) = 0.55, z = 4.76, $p < .001$). As the number of semesters in ICCR increased (i.e., timepoint), item accuracy in the treatment group increased at a significantly faster rate than in the deferred treatment/usual care control group (B(SE) = 0.09(0.04), Pred. Prob. = 0.52, $z = 2.65$, $p < .01$), suggesting an overall effect of treatment. Participants with TBI performed worse than participants with non-TBI at baseline, although this difference was not significant (B(SE) = -0.07 (0.34), Pred. Prob. = 0.48, z = -0.21, $p = .84$).

Although etiology was not a significant predictor of overall item accuracy, a follow-up analysis was conducted to specifically test for differences in the intervention effect by etiology. The three-way interaction of timepoint, group (reference level = Group), and etiology (reference level = not-TBI) was used to predict overall item accuracy with the same random effects structure as in the previous BG models (i.e. random intercepts for participant and item, by-participant random slopes for timepoint). The interaction term was not a significant predictor of overall item accuracy (B(SE) = -0.11(0.07), z = -1.50, $p = .13$), suggesting that the overall intervention benefits were similar for individuals with TBI and non-TBI. Full parameter estimates for this model are reported in Supplemental Section 4.

Effect of timepoint by subdomain and group

Adding the two-way interaction significantly improved model fit relative to the overall model (BG2 relative to BG1: $\chi^2(18) = 360.08$, $p < .001$), indicating that there were significant differences between subdomains. Expanding the model to include the three-way interaction term significantly improved model fit (BG3 relative to BG2: $\chi^2(18) = 171.83$, $p < .001$), indicating significant differences between the groups over time at the subdomain level. Full parameter estimates for BG2 and BG3 models are available in Supplemental Section 4.

Intercept and slope estimates for each subdomain are reported in Table 3 (see Supplemental Section 4 for code used to extract these values from the BG3 model). Item accuracy increased at a significantly faster rate over time for treatment participants than deferred treatment/usual care control participants in verbal expression (B(SE) = 0.18 (0.05), Pred. Prob. = 0.05, $z = 3.35$, adjusted $p < .01$). Treatment participants also improved at a significantly faster rate over time than control participants in written expression (B(SE) = 0.20(0.08), Pred. Prob. = 0.05, $z = 2.54$, $p = .011$, adjusted $p < .056$) and visuospatial/constructional (B(SE) = 0.19 (0.08), Pred Prob. = 0.05, z = 2.31, $p = .021$, adjusted $p = .069$), although these did not survive multiple comparison correction.

Within-group analyses

Treatment Group

Overall effect of treatment

As reported in Table 4, as the number of semesters in ICCR increased (i.e. timepoint), item accuracy significantly increased (B(SE) = 0.12(0.02), Pred. Prob. = 0.53, $z = 5.04$, $p < .001$), suggesting an overall effect of treatment. Participants with TBI performed slightly worse than participants with non-TBI, although this difference in item

accuracy was not significant at baseline (B(SE) = -0.48(0.38), Pred. Prob. = 0.38, z =-1.28, p = .20).

Effect of treatment by subdomain

Adding independent intercept terms for subdomains significantly improved model fit relative to the overall treatment model (WG2 relative to WG1: $\chi^2(9) = 282.24$, $p < .001$), indicating that there were significant differences in accuracy between subdomains. Adding independent slope terms for subdomains significantly improved model fit (WG3 relative to WG2: $\chi^2(9) = 63.14$, $p < .001$), indicating significant differences in treatment effects across the subdomains. Full parameter estimates for WG2 and WG3 models for the treatment group are available in Supplemental Section 5.

Intercept and slope estimates for each subdomain are reported in Table 4 and demonstrated in Figure 5a (see Supplemental Section 5 for code used to extract these values from the WG3 model). Item accuracy increased significantly over time in the verbal expression (B(SE) = 0.21(0.03), Pred. Prob. = 0.05, z = 7.07, adjusted $p < .001$), written expression (B(SE) = 0.15(0.04), Pred. Prob. = 0.04, z = 4.01, adjusted $p < .01$), memory (B(SE) = 0.15(0.03), Pred. Prob. = 0.04, z = 4.97, adjusted $p < .001$), and problem solving (B(SE) = 0.22(0.06), Pred. Prob. = 0.05, z = 3.69, adjusted $p < .01$) subdomains.

Deferred Treatment Control/Usual Care Group

Overall effect of time

As reported in Table 5, as the number of semesters in the deferred treatment/usual care control group increased (i.e. timepoint), item accuracy did not significantly increase (B(SE) = 0.04(0.05), Pred. Prob. = 0.51, z = 0.74, $p > .05$). Participants with TBI performed

591 slightly better than participants with non-TBI, although this difference in item accuracy
592 was not significant (B(SE) = 0.37(0.39), Pred. Prob. = 0.59, z = 0.96, p > .05).

593 **Overall effect of time by subdomain**

594 Adding independent intercept terms for subdomains significantly improved model
595 fit (WG2 relative to WG1: $\chi^2(9) = 318.15$, $p < .001$), indicating that there were significant
596 differences in accuracy between subdomains. Adding independent slope terms for
597 subdomains did not significantly improve model fit (WG3 relative to WG2: $\chi^2(9) = 15.30$,
598 $p = .08$), indicating only minimal rate of change differences across the subdomains. Full
599 parameter estimates for WG2 and WG3 models for the deferred treatment/usual care
600 control group are available in Supplemental Section 5. Although the subdomain*timepoint
601 interaction was only marginally statistically significant, to thoroughly assess for any
602 evidence in support of the alternative hypothesis (i.e., controls performing significantly
603 better over time in some domains), intercept and slope estimates for each subdomain are
604 reported in Table 5 and demonstrated in Figure 5b (see Supplemental Section 5 for code
605 used to extract these values from the WG3 model). The auditory comprehension
606 subdomain was the only subdomain that showed significant improvement over time
607 (B(SE) = 0.18 (0.08), Pred. Prob = 0.04, z = 2.30, p = 0.02, adj. p = .19), although this
608 difference did not survive correction.

609 Figure 6 shows the baseline accuracies and rates of change across subdomains
610 for the treatment and deferred treatment control groups. In both groups, there was a
611 moderate correlation with baseline accuracy and rate of change (Treatment group: r =
612 0.30, $t(8)$= 0.90, p > .05; Deferred Treatment/Usual Care Control group: r = 0.26, $t(8)$=

613 0.77 $p > .05$), but neither of which were significant and their interpretation is limited by
614 restricted range (i.e., most subdomains had baseline accuracy around 0.90).

615 **Discussion**
616
617 There were several findings in this study. First, as hypothesized, there was an
618 overall effect of treatment: as the number of semesters in ICCR increased, overall item
619 accuracy increased at a significantly faster rate for the treatment group than the deferred
620 treatment/usual care control group, irrespective of domain. These results support a
621 cumulative benefit of ICCR on language and other cognitive function and extend findings
622 of an initial efficacy study (Gilmore et al. 2019) to a larger sample of young adults with
623 ABI. Second, individuals with TBI and non-TBI demonstrated similar overall benefits of
624 the intervention, an important consideration given young adults with stroke may struggle
625 to find a rehabilitation peer group. Third, item accuracy in the verbal expression
626 subdomain improved at a significantly faster rate for the treatment group than the deferred
627 treatment/usual care control group, suggesting some specificity to the intervention effect.
628 Finally, within-group analyses revealed that the treatment group significantly improved in
629 verbal expression, written expression, problem solving, and memory, while the deferred
630 treatment control participants did not. Overall, these results emphasize that the
631 integration of impairment-based retraining of language and other cognitive skills with
632 “real-world” application in academically-focused activities promoted gains in underlying
633 cognitive processes (e.g., verbal expression) as measured via standardized assessment
634 items—a central tenet of the ICCR program.

635 The between-group subdomain analyses are promising in that treatment
636 participants improved at a significantly faster rate than deferred treatment control/usual

637 care control participants in the verbal expression subdomain with significant gains also
638 being observed in the written expression and visuospatial/constructional subdomains that
639 did not withstand multiple comparison correction. These subdomain level results
640 underscore the benefits of the intensive cognitive communication rehabilitation on specific
641 cognitive domains that are 1) relied upon for academic success; 2) often impaired in
642 individuals with ABI; and 3) reported to impact academic performance for individuals with
643 ABI.

644 The faster rate of improvement in verbal expression for the treatment than control
645 group is encouraging given the strong emphasis on the importance of oral communication
646 for academic success in the broader education literature (Hargie, 2006; Mahmud, 2014;
647 Morreale & Pearson, 2008; Rubin & Graham, 1988). Verbal expression activities in the
648 classroom, such as giving presentations and participating in group discussions, have
649 been associated with academic achievement in college, with studies showing that
650 students with strong oral communication have higher GPAs (Mahmud, 2014). As a next
651 step, it will be important to follow ICCR participants long-term to assess for a relationship
652 between gains in specific cognitive domains, like verbal expression, and subsequent
653 college enrollment and completion of a semester. It will also be valuable to investigate
654 potential catalysts for the robust gains observed in verbal expression in the treatment
655 group in order to support replicability of this finding in the future. On the other hand, it is
656 wholly possible that the gains in verbal expression were driven by the sum of the
657 intervention's parts as opposed to any one individual component of the intervention on its
658 own, especially given that treatment was delivered in the context of a cohort. In fact,
659 evidence from group process suggests that bringing these young adults together into a

peer group would 1) lead to increased psychosocial support and increased confidence and 2) that these gains would in turn spur increased communication initiation, and ultimately, result in increased accuracy on items in the verbal expression subdomain (DeDe et al., 2019; Elman, 2006; Elman & Bernstein-Ellis, 1999; Fama et al., 2016; Griffin-Musick et al., 2020; van der Gaag et al., 2005). Given the potential benefit for verbal expression and psychosocial functioning, it is clear that future studies of the ICCR program's efficacy should explore quantitative and qualitative benefits of the group context on verbal expression at the impairment (e.g., discourse-level metrics examining peer-to-peer interaction during class discussion), activity/participation (e.g., frequency of self-initiated social interaction between classes), and quality of life levels (e.g., satisfaction and confidence during peer-to-peer communication in classroom discussion).

Despite these positive outcomes, there does appear to be some specificity to the effect of the intervention as treatment participants' item accuracy did not improve at a significantly faster rate than deferred treatment/usual care controls for all subdomains targeted by the intervention (i.e., auditory comprehension, reading comprehension, attention, orientation, problem solving, upper limb/facial/instrumental apraxia). There are several potential reasons for this result. First, attention showed no change between or within groups as evidenced by flat slope estimates (Between Group: B(SE) = 0.01 (0.07); Treatment Group: B(SE) = -0.01 (0.03); Control Group: B(SE) = 0.01(0.07)). It is possible that attention may have required more domain-specific intervention to demonstrate improvement on neuropsychological assessments of this subdomain (e.g., direct attention training; Sohlberg et al., 2000). Second, deferred treatment/usual care control participants demonstrated larger slopes than treatment participants for several domains,

683 leading to a negative between-group estimate for that subdomain (i.e., orientation,
684 problem solving, auditory comprehension). Deferred treatment controls showed the
685 steepest slope for the orientation subdomain (B(SE) = 0.37 (0.35)), but treatment
686 participants also showed a positive slope in this domain (B(SE) = 0.28 (0.15)). Across
687 groups, the orientation estimate was accompanied by the largest standard error (Between
688 group: B(SE) = -0.09 (0.38)), indicating there was greater variability in predictions for this
689 subdomain. The orientation subdomain had fewer items and points possible than the
690 other subdomains (see Figure 3), which likely led to greater uncertainty in the predictions
691 for this subdomain (i.e., logistic models take into consideration the number of trials —
692 another advantage of the GLMM approach used in this study). Both groups showed
693 positive slopes in auditory comprehension and problem solving, explaining the non-
694 significant effect between groups for these domains. Finally, the intervention did appear
695 to have some positive effect on the reading comprehension (Between Group: B(SE) =
696 0.11 (0.07); Treatment Group: B(SE) = 0.10 (0.03); Control Group (B(SE) = 0.01(0.08))
697 and upper limb/facial/instrumental apraxia function (Between Group: (SE) = 0.20 (0.15);
698 Treatment Group: B(SE) = 0.07 (0.06); Control Group: (B(SE) = -0.11 (0.14)), although
699 these effects did not reach statistical significance. Overall, the subdomain analyses are
700 promising and will serve to inform the development of future studies investigating the
701 efficacy of the ICCR program.

702 Beyond the domain-specific gains, the overall treatment effect of this intensive,
703 comprehensive cognitive rehabilitation program generates a larger question for
704 neurorehabilitation - what is driving the significant recovery of language and other
705 cognitive function in this chronic young ABI population? The neuroplasticity literature

706 would suggest that the repetitive, intensive, salient training within the academic context
707 was responsible for the gains (Kiran & Thompson, 2019; Kleim & Jones, 2008). Recent
708 studies investigating intensity and dosage in CR (Brady et al., 2016; Königs et al., 2018)
709 would support that it was the roughly 240 hours delivered per ICCR semester that spurred
710 the participants' improvements in this study. The intervention incorporated evidence-
711 based cognitive rehabilitation approaches, such as, one-on-one language therapy and
712 group-based metacognitive strategy training for executive function. It also employed
713 academic material as the vehicle for therapy, which aligns with contextualized cognitive
714 rehabilitation targeting language and other cognitive process in the context where the
715 breakdown occurs (i.e., academic activities). Finally, ICCR is a comprehensive, multi-
716 modal cognitive rehabilitation program in line with a recent systematic review that
717 recommended neuropsychological rehabilitation to reduce cognitive and functional
718 disability after TBI or stroke (Cicerone et al., 2019). It was likely the integration of these
719 components: 1) principles of neuroplasticity such as intensity, repetition, and salience; 2)
720 evidence-based individual and group cognitive rehabilitation; and 3) contextualized
721 skill/strategy training and application that promoted cognitive recovery for young adults
722 with chronic ABI in the present study. Further regarding the benefit of this last component
723 of the program, ICCR targeted language and other cognitive domains within a functional
724 setting (i.e., simulated college class), which transferred to item-level gains on
725 standardized assessments of cognitive function proximal to the intervention. This finding
726 is promising regarding the transfer of gains from integrated cognitive rehabilitation to other
727 contexts. An important next step will be to assess the extent to which these gains in

language and other cognitive function lead to successful enrollment in college for young adults with ABI in future work.

Within-group analyses were implemented in this study to identify subdomains that were responsive to change due to treatment and non-treatment factors. As shown in Figures 5 and 6, the verbal expression, written expression, memory, and reading comprehension subdomains significantly improved in the treatment group over time (at the original $p < .05$ level). The opposite pattern was observed in the deferred treatment/usual care control group for those subdomains. Taken together, this pattern underscores that verbal expression, written expression, memory and reading comprehension domains were stimulable to the intervention. Future work should investigate what specific components of ICCR are associated with gains in these specific subdomains (e.g., weekly practice quiz scores and gains in the memory subdomain) and begin to identify the active ingredients of this multi-faceted intervention. Additionally, problem solving and orientation showed a similar pattern of improvement in both groups, suggesting that these gains may have been associated with non-treatment factors (e.g., outpatient therapy, work, volunteer, practice effects). The significant effect of timepoint for the problem solving domain observed in the treatment group should therefore be interpreted with some caution and would benefit from further investigation in future work.

Recall, etiology was included as a covariate in all of the analyses, but never significantly predicted item accuracy. To address any residual concern about including individuals with non-traumatic and traumatic brain injury in the same intervention—anticipated given the common separation of interventions for individuals with stroke and TBI in the speech-language pathology field—a final between-group model was fit to the

751 data using the interaction of timepoint-by-group-by-etiology to predict overall item
752 accuracy. The interaction estimate was not significant, meaning the effect of the
753 intervention was similar for individuals with non-TBI and TBI. This finding is important
754 because young adults with post-stroke aphasia often lack a rehabilitation peer group as
755 most stroke survivors are older (Benjamin et al., 2019) and may have different long-term
756 rehabilitation goals. Combining across these two ABI etiologies within an intervention
757 would provide young stroke survivors a peer group with similar goals (e.g., post-
758 secondary education) as young adults are a frequently affected age group to sustain TBI
759 (i.e., ages 15-24; Taylor, 2017). Further, similar effects of the intervention across
760 etiologies may encourage clinical practice to move away from separating the cognitive
761 impairments observed after stroke and TBI according to etiology (Coelho et al., 1996,
762 2005; Frey, 2020; Norman et al., 2013; Turkstra et al., 2005) toward considering the
763 cognitive deficit profile of patients regardless of etiology when planning assessment and
764 intervention. Of note, no major limitations were observed in combining young adults with
765 traumatic and non-traumatic etiologies in the same intervention. In fact, combining the
766 etiologies provided natural teaching moments for clinicians to emphasize that all of the
767 individuals in the program had areas of strength and areas for growth, while also
768 empowering individuals to support one another in ways that they could be successful. For
769 example, participants with stroke-induced aphasia were able to support individuals with
770 memory impairment after TBI by recalling a fact or showing them where to find information
771 reviewed earlier. As a complement, individuals with memory impairment after TBI were
772 able to support individuals with stroke-induced aphasia during times of word retrieval
773 difficulty. Nevertheless, it will be important to add to these clinician-generated benefits by

774 investigating the participants' perceptions and experiences of being grouped with others
775 with different brain etiologies in future studies to ensure a complete perspective.

776 Unlike that of etiology, the influence of time post onset and ABI severity on
777 treatment outcomes was not formally examined. In terms of time post onset, all
778 participants in this study were in the chronic phase of recovery and thus, outside the
779 window when the majority of spontaneous recovery is believed to occur. Moreover,
780 previous studies have not found treatment outcomes in the chronic phase to be influenced
781 by time post onset (Doogan et al. 2018, Moss & Nicholas, 2006, Holland et al. 2017,
782 Turner-Stoke, 2008) and thus, time post onset was not included as a covariate in the
783 present study. In regards to severity, ABI severity is not accurately captured through one
784 single standardized assessment measure (e.g., WAB-AQ, RBANS-Total) and for reasons
785 of multicollinearity, it would have been inappropriate to include multiple metrics. Thus, this
786 study focused on first acquiring a robust understanding of impairments across a range of
787 language and other cognitive processes (e.g., attention, memory) in young adults with
788 ABI, while accounting for variance in performance based on the nature of their injury.
789 Further, it is unlikely that severity played a role in the difference in overall treatment effect
790 between the groups as 1) there were similar proportions of individuals with mild,
791 moderate, severe language and cognitive impairment in both groups (see Table 1); 2) the
792 treatment participant group demonstrated more severe impairment than the deferred
793 treatment control group at the first timepoint, but improved at faster rate (see Figure 4);
794 and 3) subdomain level results reveal the absence of a ceiling effect (e.g., some domains
795 with high starting accuracy improved significantly over time, some domains with low
796 starting accuracy remained stable over time; Figure 6). Future studies of the ICCR

program with larger participant samples will be better-equipped to identify predictors of treatment success, which are likely to be multifactorial (e.g., severity, family support, motivation) as opposed to unitary in nature (i.e., ABI severity).

Despite the encouraging results of the present study and previous work (Gilmore et al. 2019), there is much about the ICCR program that requires further exploration. First, these gains in language and other cognitive function may have been supported by changes in the brain. Future studies should test this hypothesis by assessing to what extent there are brain changes before and after intervention and whether those changes are associated with gains in cognitive function. Longitudinal neuroimaging studies of this nature have the potential to inform future models of rehabilitation-induced recovery. Second, it will be important to conduct studies that elucidate the active ingredients of the ICCR program and begin to answer more fine-grained questions about intensity, dosage, and other principles of learning. Third, larger group studies will allow for the systematic investigation of factors (e.g., family support) that promote a positive response to the intervention, including eventual return to and success in college. Finally, to date, a number of treatment participants have enrolled in college post-program (i.e., nine of fifteen possible), but only one control participant (i.e., out of ten possible) has pursued enrollment. It will be essential in future studies to more systematically investigate long-term outcomes by determining the extent to which ICCR participants enroll in college immediately post-program and then, go on to successfully complete a semester of college.

Conclusion

The results of this study revealed an overall effect of the ICCR program, and specifically, that treatment participants significantly improved in verbal expression at a faster rate than deferred treatment/usual care control participants. At the within-group level, treatment participants demonstrated significant longitudinal gains in memory, verbal expression, written expression and problem solving, while deferred treatment/usual care control participants showed no significant longitudinal gains at the overall item or subdomain item level. These results emphasize the efficacy of this novel, intensive, comprehensive cognitive rehabilitation program in the largest participant sample to date. Further, this study's findings provide strong evidence that integrating impairment-based retraining of language and other cognitive skills with "real-world" application in academically-focused activities promotes change in underlying cognitive processes as measured by standardized assessment items—an impetus for a paradigm shift from typical rehabilitation for young adult ABI survivors.

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Table Captions

Table 1. Demographic Details

Caption: *Note.* MPO = months post onset of injury, ABI = acquired brain injury, TBI = traumatic brain injury, Non-TBI = non-traumatic brain injury, WAB-R AQ = Western Aphasia Battery – Revised Aphasia Quotient (WAB-R AQ; Kertesz, 2006; < 93.8 suggests presence of language impairment), Repeatable Battery for the Assessment of Neuropsychological Status (RBANS-Total; Randolph, 2012; Mean = 100, SD = 15)
* = Participant started as a deferred treatment/usual care control participant and transitioned to the treatment group.

Table 2. Detailed description of ICCR program components

Table 3. Main results of the generalized linear mixed effects regression analyses comparing the treatment group to the deferred treatment/usual care control group

Caption: *Note*. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; "Prob."), Adj. = p-values for the domain-specific slopes were adjusted using the Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-timepoint = "0"; Post-timepoint 1 = "1", Post-timepoint 2 = "2", Post-timepoint 3 = "3." Etiology was dummy-coded (i.e., TBI and NTBI) with NTBI as the reference level. Group was dummy-coded with control as the reference level. Sub-Domain was dummy-coded with attention as the reference level.

Table 4. Main results of the generalized linear mixed effects regression analyses for the treatment group

Caption: *Note*. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; "Prob."), Adj. = p-values for the domain-specific slopes were adjusted using the Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-treatment = "0"; Post-treatment 1 = "1", Post-treatment 2 = "2", Post-treatment 3 = "3." Etiology was dummy-coded (i.e., TBI and NTBI) with NTBI as the reference level. Sub-Domain was dummy-coded with attention as the reference level.

Table 5. Main results of the generalized linear mixed effects regression analyses for the deferred treatment/usual care control group only

Caption: *Note*. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; "Prob."), Adj. = p-values for the domain-specific slopes were adjusted using the

Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-timepoint 1 = “1”, Post-timepoint 2 = “2. Etiology was dummy-coded (i.e., TBI and NTBI) with NTBI as the reference level. Sub-Domain was dummy-coded.

Figure Captions

Figure 1. Flow diagram for recruitment, enrollment, self-grouping, and analysis
Caption: * = Data from both of their study phases were included in the analyses. See "Model Building Structure" section in Methods for how these data were managed.

Figure 2. Sample Intensive Cognitive and Communication Rehabilitation program weekly schedule
Caption: N/A

Figure 3. Item assignment to sub-domains
Caption: Comp. = comprehension; Apraxia = items from WAB-R Apraxia subtest that measures upper limb, facial, instrumental, and complex actions

Figure 4. Overall of treatment by group
Caption: Plots reveal performance on overall items by group. Open circles = individual participant means, filled points = group means + SE, solid lines = model predicted group means.

Figure 5a. Effect of timepoint by sub-domain for the treatment group

Figure 5b. Effect of timepoint by sub-domain for the deferred treatment control/usual care group
Caption: Plot reveals performance on individual sub-domains over time for the control participants. Open circles = individual participant means, filled points = group means + SE, solid lines = model predicted group means. Asterisks reflect significance after FDR-correction (*N.S. = > 0.10,* * = < 0.05; ** = < 0.01 ; *** = < 0.001). Crosses reflect significance at the original p-value level († = $p < 0.05$ uncorrected).

Figure 6. Scatterplot showing relationship between intercept and slope estimate for each sub-domain for each of the groups
Caption: Treatment group scatterplot is in the left panel and deferred treatment/usual care control group scatterplot is in the right panel. Horizontal line reflects the predicted improvement in accuracy after one semester of the intensive intervention and/or one semester of deferred treatment/usual care based on the slope estimate for that sub-domain.

Supplemental File Description

Supplemental Section 1. This section details what activities the deferred treatment/usual care control participants engaged in during the study.

Supplemental Section 2. This section provides a table with subtest scores for the standardized assessment battery (i.e., WAB-R, RBANS, SCCAN, DCT) for all participants.

Supplemental Section 3. This section explains the process for assigning standardized assessment items to a subdomain when their subtest name did not clearly match one of the ten subdomains.

Supplemental Section 4. This section provides parameter estimates for between-group GLMMS that were conducted as part of the model building process. These models were used to test the need to increase the complexity of the model structure, but do not answer the primary research question and thus, their results are included in the supplemental section for full transparency. This section also provides the R code that was used to extract the domain-specific intercepts and slopes reported in the paper.

Supplemental Section 5. This section provides parameter estimates for within-group GLMMS that were conducted as part of the model building process. These models were used to test the need to increase the complexity of the model structure, but do not answer the primary research question and thus, their results are included in the supplemental section for full transparency. This section also provides the R code that was used to extract the domain-specific intercepts and slopes reported in the paper.

Table 1.

Demographic Details

Treatment Participants												
ID	Age	Sex	MPO at enroll-ment	ABI Etiology Broad	ABI Etiology Specific	Education Level	WAB-AQ	Severity of Lang. Impair-ment	RBANS-Total	Severity of Cog. Impair-ment	N of Timepo ints Contrib uted	Premorbid MH or LD Dx
P1	24.09	F	99.02	NTBI	Tumor	13	81.8	Mild	44	Severe	4	No
P2	29.16	M	70.2	NTBI	Stroke	15	78.8	Mild	64	Mod	4	No
P3	24.64	F	44.25	NTBI	Stroke	16	58.7	Mod	44	Severe	2	No
P4	21.01	M	49.28	TBI	TBI	12	61.9	Mod	45	Severe	4	No
P5	25	M	96.06	TBI	TBI	12	62.5	Mod	46	Severe	4	No
P6	35.21	M	97.24	TBI	TBI	16	18.8	Very severe	47	Severe	2	No
P7	22.12	F	14.95	TBI	TBI	14	93.8	Mild	78	Mild	4	No
P8	27.53	M	13.14	TBI	TBI	14	96.8	WNL	59	Mod	2	Yes, MH
P9	25.35	M	68.86	TBI	TBI	12	67.5	Mod	49	Severe	4	No
P10	29.67	M	97.77	NTBI	Stroke	15	87.5	Mild	52	Severe	4	Yes, MH
P11	25.73	M	35.68	TBI	TBI	15	90.6	Mild	53	Severe	4	No
P12	21.26	M	13.11	TBI	TBI	13	92.2	Mild	49	Severe	2	No
P13*	21.89	M	4.57	NTBI	Tumor	15	94.2	WNL	52	Severe	4	Yes, LD
P14*	20.45	M	53.88	NTBI	Stroke	13	92.8	Mild	74	Mild	4	Yes, LD
P15	18.02	F	37.02	NTBI	Stroke	12	99.6	WNL	74	Mild	4	No
P16	21.55	M	19.97	NTBI	Tumor	14	97.2	WNL	68	Mod	4	Yes, LD
P17*	25.37	M	144.94	NTBI	Encephalitis	12	96.5	WNL	60	Mod	4	No
P18*	20.5	F	22.24	NTBI	Tumor	13	65	Mod	46	Severe	3	No
P19*	21.04	M	18.53	TBI	TBI	12	43.7	Severe	45	Severe	3	No
P20	22.17	F	31.34	NTBI	Stroke	12	65.6	Mod	45	Severe	2	No
P21	18.79	F	12.02	NTBI	Stroke	12	95	WNL	63	Mod	2	No
P22*	32.81	M	99.93	TBI	TBI	18	92.6	Mild	55	Severe	2	No

Mean (SD)	24.24 (4.43)	M = 15 F = 7	52.00 (39.10)	NTBI = 12 TBI = 10	TBI = 10 Stroke = 7 Tumor = 4 Encephalitis = 1	13.64 (1.71)	78.78 (20.93)	WNL = 6 Mild = 8 Mod = 6 Severe = 1 Very Severe = 1	55.09 (10.84)	WNL = 0 Mild = 3 Mod = 5 Severe = 14 Mild = 3	3.27	No Hx = 17 MH = 2 LD = 3
Range	18.02 – 35.21		4.57 – 144.94			12 – 18	18.8 – 99.6		44 – 78		2 – 4	LD = 3

Deferred Treatment/Usual Care Control Participants												
C1	23.06	F	38.11	TBI	TBI	12	91.3	Mild	52	Severe	3	No
C2*	20.5	F	22.24	NTBI	Tumor/ hemorrhage	13	65	Mod	46	Severe	2	No
C3	30.94	M	38.47	NTBI	Stroke	23	72.1	Mod	64	Mod	2	No
C4	31.53	F	59.76	NTBI	Stroke	14	84.3	Mild	71	Mild	3	No
C5	29.61	M	158.21	TBI	TBI	12	99.5	WNL	54	Severe	3	No
C6	22.35	M	48.55	TBI	TBI	12	92	Mild	55	Severe	3	No
C7*	21.89	M	4.57	NTBI	Tumor	15	94.2	WNL	52	Severe	2	Yes, LD
C8	24.95	F	42.68	TBI	TBI	14	97.6	WNL	79	Mild	2	Yes, MH
C9	21.1	F	17.45	NTBI	Stroke	13	72.3	Mod	51	Severe	2	No
C10*	20.45	M	53.88	NTBI	Stroke	13	92.8	Mild	74	Mild	2	Yes, LD
C11*	32.81	M	99.93	TBI	TBI	18	92.6	Mild	55	Severe	3	No
C12*	25.37	M	144.94	NTBI	Encephalitis	12	96.5	WNL	60	Mod	2	No
C13*	21.04	M	18.53	TBI	TBI	12	43.7	Severe	45	Severe	3	No
C14	38.23	F	61.46	TBI	TBI	16	84.2	Mild	53	Severe	2	No
Mean (SD)	25.99 (5.64)	M = 8 F = 6	57.77 (46.27)	NTBI = 7 TBI = 7	TBI = 7 Stroke = 4 Tumor = 2 Encephalitis = 1	14.21 (3.09)	84.15 (15.73)	WNL = 4 Mild = 6 Mod = 3 Severe = 1 Very Severe = 0	57.93 (10.37)	WNL = 0 Mild = 3 Mod = 2 Severe = 9	2.43 (0.51)	No Hx = 11 MH = 1 LD = 2
Range	20.45 – 38.23		4.57 – 158.21			12 – 23	43.7 – 99.5		45 – 79		2 – 3	

Note. MPO = months post onset of injury at time of enrollment, ABI = acquired brain injury, TBI = traumatic brain injury, NTBI = non-traumatic brain injury, WAB-AQ = Western Aphasia Battery – Revised Aphasia Quotient (WAB-AQ; Kertesz, 2006; < 93.8 suggests presence of language impairment), Repeatable Battery for the Assessment of Neuropsychological Status (RBANS-Total; Randolph, 2012; Mean = 100, SD = 15). Severity of language impairment was assigned as follows: WNL: > 93.8, Mild = 93.8 – 76, Moderate = 51-75, Severe = 26 – 50, Very severe = 0 – 25, based on the WAB-R manual. Severity of cognitive impairment was assigned as follows: WNL: < 1 SD below the mean; Mild: ≥ 1 SD below the mean, but < 2 SD below the mean; Moderate: ≥ 2 SD below the mean, but less than 3 SD below the mean; Severe: ≥ 3 SD below the mean. Participants with "Yes" demarcation in the final column reported premorbid history (Hx) of mental health diagnosis (MH; e.g., attention deficit disorder, depression) or learning disability/difficulty (LD; e.g., required individualized education program in school for reading). P13/C17 was < 12 months post onset when they signed the consent form. They had an unexpected change in medical status after enrolling and thus, started their deferred treatment control phase at 15 months post onset and treatment phase at 18 months post onset.

* = Participant started as a deferred treatment/usual care control and transitioned to treatment group

Table 2.

Detailed description of ICCR program components

Component	Description	Materials	Common Clinician Support
Quiz on previous week's course content	• Each question read aloud by SLP	• 5 questions (i.e., multiple-choice, yes/no, true false, short answer)	• Repeated the questions and provided extra time, as requested
AM Lecture (e.g., Biology)	• Watch pre-recorded video	• 45 to 60 minutes of open source academic content • Laptop and projector	• Tactile, visual, and verbal cues to sustain attention and/or take notes
Lecture Review	• Discuss lecture content as a group	• Whiteboards and markers • Pre-made lecture notes for SLP, support staff, and participants	• Cues to support word retrieval, recall, and organization • Modeled and supported participants to use metacognitive strategies
Practice Quiz Questions	• Answer questions about the day's lecture content • Share answers and discuss why correct/incorrect • Location answers in the notes • Mark areas of notes to study	• Powerpoint presentation with questions from the day's lecture and answers • Laptop and projector • Response sheets for students	• Encouraged participants to use the activity to identify what they needed to study before the actual quiz the following week • Modeled and supported participants to use metacognitive strategies (e.g., rehearse, imagine, take time, activate; RITA)
PM Seminar (e.g., Personal Finance)	• Mix of discussion- and project-based activities • Questions and discussion were	• Varied by course topic (e.g., book and chapter summaries for English Literature)	• Same cues as in lecture and lecture review (e.g., cues to sustain attention, support language comprehension/

	interleaved with new content		expression, promote recall/ organization) • Constructive feedback in verbal/written form (e.g., for public speaking, essay writing)
Individual Therapy	• Target therapy goals developed with the participant and focused on their needs	• Varied by participant and/or domain • Included impairment- and functionally-based approaches	• Tactile, visual, and verbal cues, depending on the nature of the activity and participants' performance
Technology-based intervention	• Range of therapeutic (e.g., Constant Therapy) and academic activities (e.g., making flashcards on Quizlet)	• iPads • laptops • headphones • cognitive-linguistic therapy applications • Attention Process Training-3 • Google Suite	• Helped set-up the equipment • Monitored participants' performance • Provided direct intervention for challenging activities • Cues to sustain attention to task

Note. During the COVID-19 pandemic in 2020, the lectures/seminars, review sessions, practice quiz questions, and individual therapy were delivered using the Zoom platform.

Table 3.

Main results of the generalized mixed effects regression analyses comparing the treatment group to the deferred treatment/usual care control group

Model	Syntax	Term		Logit odds (SE)	Prob.	Z-value	p-value (adj.)	Random effects: Variance (SD)		
								Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Overall	glmer(cbind(obs_score, (poss_score-obs_score)) ~ Timepoint *Group + Etiology +(1+Timepoint | ID) + (1 |Item)	Intercept		1.81 (0.25)	0.86	7.11	*p* < .001	0.91 (0.96)	3.48 (1.86)	0.01(0.11); -0.27
		Timepoint		0.03 (0.03)	0.51	0.81	N.S.			
		Group, ref. level = control		0.19 (0.04)	0.55	4.76	*p* < .001			
		Etiology, ref. level = non-TBI		-0.07 (0.34)	0.48	-0.21	N.S.			
		Timepoint-by-Group		0.09 (0.04)	0.52	2.65	*p* < .01			
Sub-Domain	glmer(cbind(obs_score,(poss_score-obs_score)) ~ Timepoint * Sub-Domain*Group+ Etiology + (1+Timepoint | ID) + (1 | Item)	Auditory Comprehension		0.22				0.91	2.05	0.01(0.11);
			Intercept	(0.07)	0.55	3.01		(0.95)	(1.43)	-0.22
				-0.10	-		N.S.			
			Slope	(0.07)	0.03	-1.48	(N.S.)			
		Verbal Expression		0.04						
			Intercept	(0.06)	0.51	0.63				
				0.18			*p* < .001			
			Slope	(0.05)	0.05	3.35	(*p* < .01)			
		Reading Comprehension		-0.10						
			Intercept	(0.08)	0.48	-1.19				
				0.11			N.S.			
			Slope	(0.07)	0.03	1.44	(N.S.)			
		Written Expression		0.02						
			Intercept	(0.09)	0.51	0.26				
				0.20			.011			
			Slope	(0.08)	0.05	2.54	(.056)			
		Attention		0.30						
			Intercept	(0.08)	0.58	4.00				
				0.01			N.S.			
			Slope	(0.07)	0.00	0.12	(N.S.)			

Orientation		0.22			
	Intercept	(0.36)	0.56	0.61	
		-0.09	-		N.S.
	Slope	(0.38)	0.02	-0.24	(N.S.)
Memory		0.25			
	Intercept	(0.07)	0.56	3.62	
		0.12			.054
	Slope	(0.06)	0.03	1.93	(.135)
Problem Solving		0.44			
	Intercept	(0.14)	0.61	3.12	
		-0.04	-		N.S.
	Slope	(0.13)	0.01	-0.29	(N.S.)
Visuospatial/Constructional		0.74			
	Intercept	(0.09)	0.68	8.10	
		0.19			.021
	Slope	(0.08)	0.05	2.31	(.069)
Upper Limb/Facial/Instrumental Apraxia		0.13			
	Intercept	(0.16)	0.53	0.82	
		0.20			N.S.
	Slope	(0.15)	0.05	1.38	(N.S.)

Note. obs_score = s *Note*. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; “Prob.”), Adj. = p-values for the domain-specific slopes were adjusted using the Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-timepoint = “0”; Post-timepoint 1 = “1”, Post-timepoint 2 = “2”, Post-timepoint 3 = “3.” Etiology was dummy-coded (i.e., TBI and non-TBI) with non-TBI as the reference level. Group control as the reference level. Sub-Domain was dummy-coded with attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Table 4.

Main results of the generalized linear mixed effects regression analyses for the treatment group

Model	Syntax	Term		Logit odds (SE)	Prob.	Z-value	p-value (adj.)	Random effects: Variance(SD)		
								Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Overall model	glmer(cbind(obs_score, (poss_score-obs_score)) ~ Timepoint + Etiology + (1+Timepoint | ID) + (1 |Item)	Intercept		2.01 (0.28)	0.88	7.24	$p < .001$	0.94 (0.97)	3.52 (1.88)	0.01 (0.10); -0.42
		Timepoint		0.12 (0.02)	0.53	5.04	$p < .001$			
		Etiology, ref. level = non-TBI		-0.48 (0.38)	0.38	-1.28	N.S.			
Sub-Domain	glmer(cbind(obs_score,(poss_score-obs_score)) ~ Timepoint* Sub-Domain + Etiology + (1+Timepoint | ID) + (1 | Item)	Auditory Comprehension	Intercept	2.77 (0.30)	0.94	9.21		0.92 (0.96)	2.11 (1.45)	0.01 (0.09); -0.37
			Slope	0.06 (0.03)	0.01	1.84	N.S. (N.S.)			
		Verbal Expression	Intercept	2.13 (0.32)	0.89	6.73				
			Slope	0.21 (0.03)	0.05	7.07	$p < .001$ ($p < .001$)			
		Reading Comprehension	Intercept	2.10 (0.31)	0.89	6.79				
			Slope	0.10 (0.03)	0.02	2.89	.03 (.06)			
		Written Expression	Intercept	2.33 (0.39)	0.91	5.89				
			Slope	0.15 (0.04)	0.04	4.01	$p < .01$ ($p < .01$)			
		Attention	Intercept	0.59 (0.48)	0.64	1.23				
			Slope	-0.01 (0.03)	0.00	-0.31	N.S. (N.S.)			
		Orientation	Intercept	3.27 (0.54)	0.96	6.05				
			Slope	0.28 (0.15)	0.07	1.86	N.S. (N.S.)			

Memory	Intercept	-0.09 (0.30)	0.48	-0.31	
	Slope	0.15 (0.03)	0.04	4.97	$p < .001$ ($p < .001$)
Problem Solving	Intercept	3.40 (0.34)	0.97	10.00	
	Slope	0.22 (0.06)	0.05	3.69	$p < .01$ ($p < .01$)
Visuospatial/Constructional	Intercept	1.56 (0.38)	0.83	4.10	
	Slope	0.10 (0.04)	0.03	2.56	.08 (N.S.)
Upper Limb/Facial/Instrumental Apraxia	Intercept	3.10 (0.43)	0.96	7.16	
	Slope	0.07 (0.06)	0.02	1.16	N.S. (N.S.)

Note. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; "Prob."), Adj. = p-values for the domain-specific slopes were adjusted using the Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-treatment = "0"; Post-treatment 1 = "1", Post-treatment 2 = "2", Post-treatment 3 = "3." Etiology was dummy-coded (i.e., TBI and non-TBI) with non-TBI as the reference level. Sub-Domain was dummy-coded with attention as the reference level. The correlation value refers to the strength of the association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

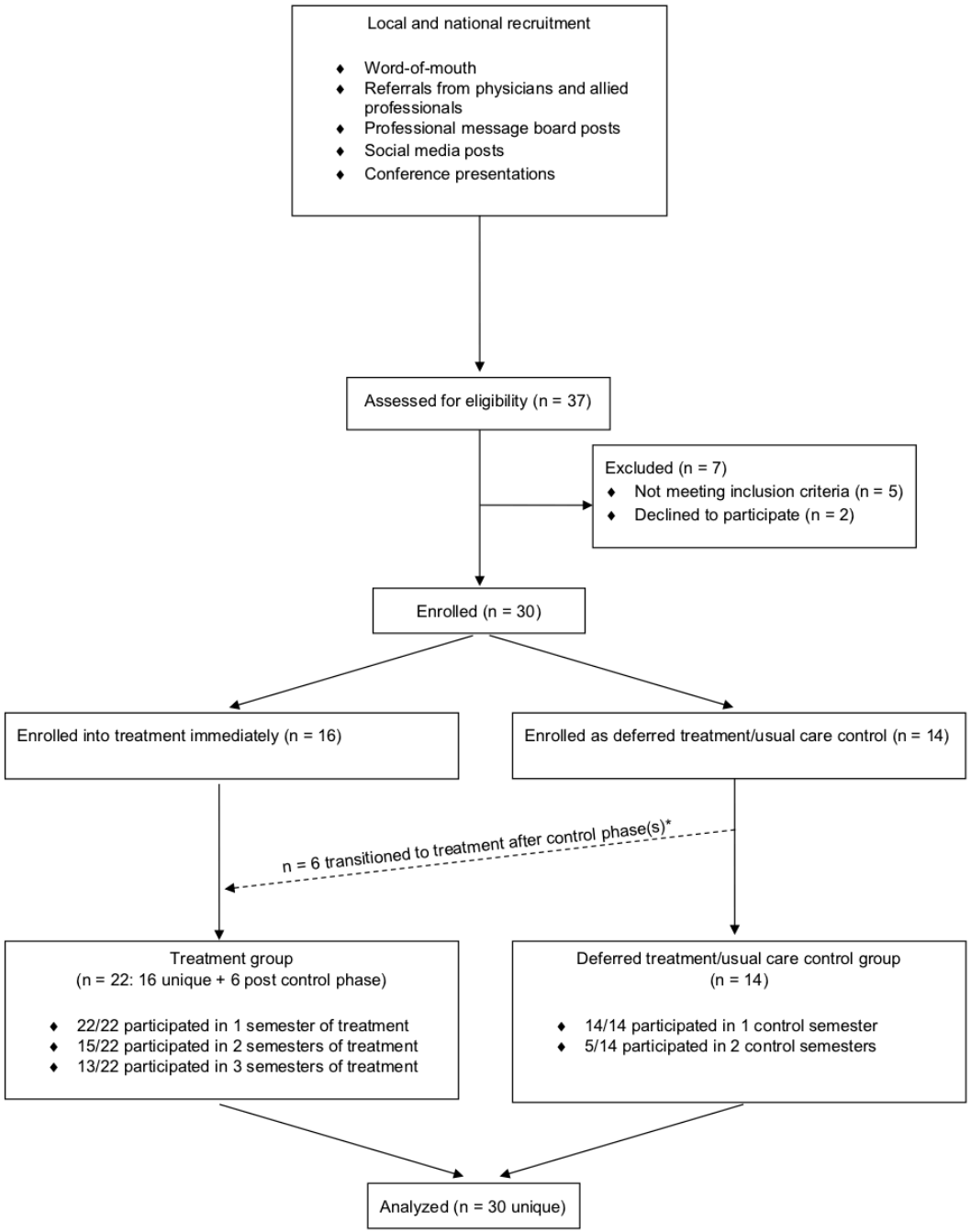
Table 5.

Main results of the generalized linear mixed effects regression analyses for the deferred treatment/usual care control group

Model	Syntax	Term		Logit odds (SE)	Prob.	Z-value	p-value (adj.)	Random effects: Variance(SD)		
								Intercept: ID	Intercept: Item	Slope: Time-by-ID;Corr
Overall	glmer(cbind(obs_score, (poss_score-obs_score)) ~ Timepoint + Etiology + (1+Timepoint | ID) + (1 |Item)	Intercept		2.00 (0.30)	0.88	6.684	$p < .001$	0.64(0.80)	3.76(1.94)	0.03(0.18); -0.57
		Timepoint		0.04 (0.05)	0.51	0.735	N.S.			
		Etiology, ref. level = non-TBI		0.37 (0.39)	0.59	0.96	N.S.			
	glmer(cbind(obs_score,(poss_score-obs_score)) ~ Timepoint* Sub-Domain + Etiology + (1+Timepoint | ID) + (1 | Item)	Auditory Comprehension	Intercept	2.69 (0.32)	0.94	8.41		0.64(0.80)	1.91(1.38)	0.03(0.17); -0.54
			Slope	0.18 (0.08)	0.04	2.30	$p < .05$ (N.S.)			
		Verbal Expression	Intercept	2.47 (0.34)	0.92	7.37				
			Slope	0.04 (0.07)	0.01	0.64	N.S. (N.S.)			
		Reading Comprehension	Intercept	2.29 (0.33)	0.91	6.97				
			Slope	0.01 (0.08)	0.00	0.14	N.S. (N.S.)			
		Written Expression	Intercept	2.52 (0.41)	0.93	6.10				
			Slope	-0.04 (0.08)	-0.01	-0.44	N.S. (N.S.)			
		Attention	Intercept	0.09 (0.50)	0.52	0.18				
			Slope	0.01 (0.07)	0.00	0.09	N.S. (N.S.)			
		Orientation	Intercept	3.17 (0.59)	0.96	5.39				
			Slope	0.37 (0.35)	0.09	1.07	N.S. (N.S.)			

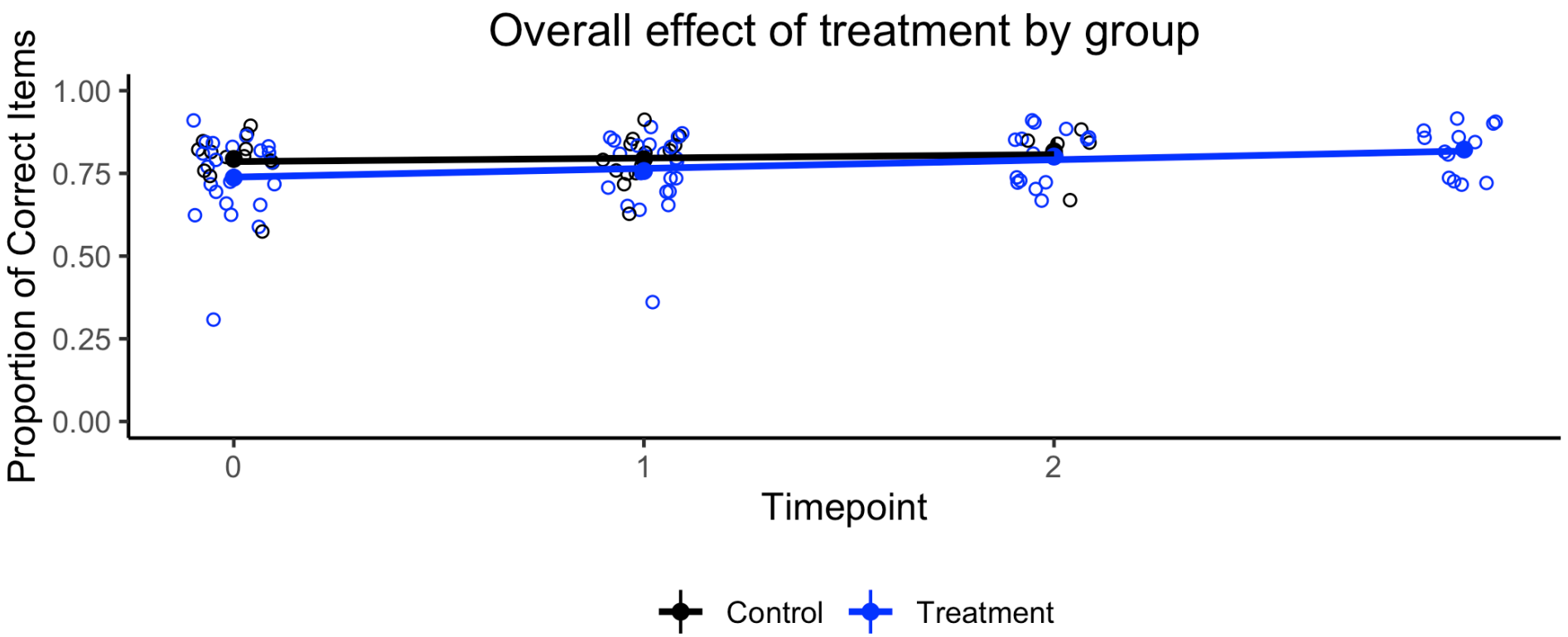
Memory		-0.24			
	Intercept	(0.32)	0.44	-0.74	
		0.06			N.S.
	Slope	(0.07)	0.01	0.85	(N.S.)
Problem Solving		2.81			
	Intercept	(0.36)	0.94	7.85	
		0.24			
	Slope	(0.12)	0.06	1.94	.05 (N.S.)
Visuospatial/Constructional		0.83			
	Intercept	(0.39)	0.70	2.13	
		-0.07			N.S.
	Slope	(0.08)	-0.02	-0.88	(N.S.)
Upper		3.25			
Limb/Facial/Instrumental	Intercept	(0.45)	0.96	7.20	
Apraxia		-0.11			N.S.
	Slope	(0.14)	-0.03	-0.80	(N.S.)

Note. obs_score = score obtained for item, poss_score = maximum possible score for item, ref = reference, SE = standard error, ID = participant, Logit odds were converted to odds ratios and then, to probability values (i.e., proportion of items correct; "Prob."), Adj. = p-values for the domain-specific slopes were adjusted using the Benjamini-Hochberg (BH) method. Timepoint was coded as a numeric predictor: Pre-timepoint = "0"; Post-timepoint 1 = "1", Post-timepoint 2 = "2." Etiology was dummy-coded (i.e., TBI and non-TBI) with non-TBI as the reference level. Sub-Domain was dummy-coded with attention as the reference level. The correlation value refers to the strength of the association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

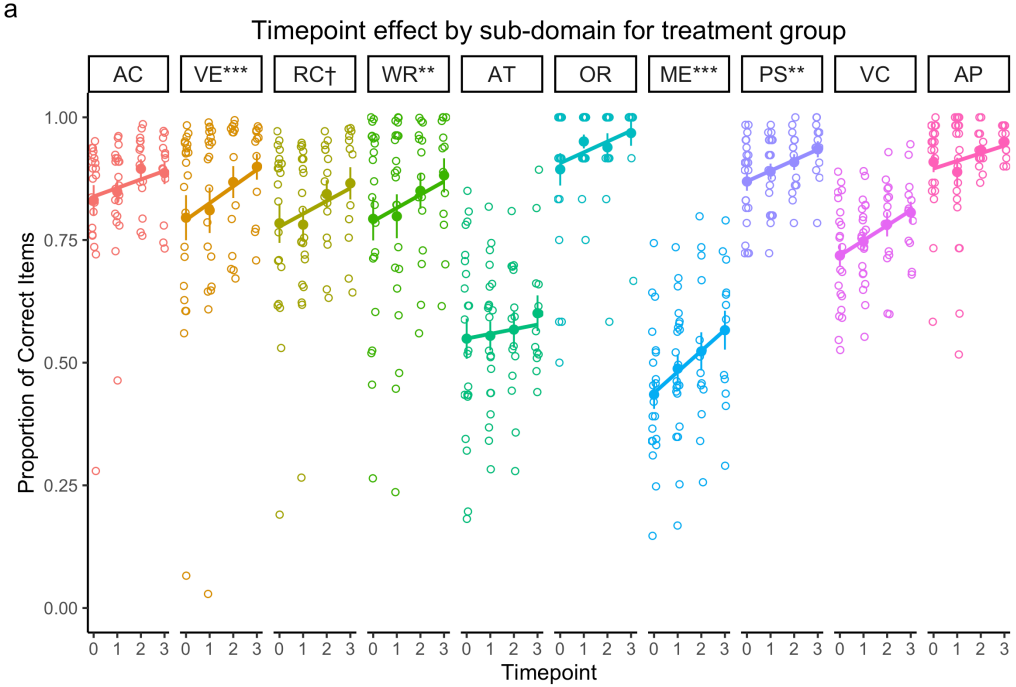

Local and national recruitment
Word-of-mouth
Referrals from physicians and allied professionals
Professional message board posts
Social media posts
Conference presentations
Assessed for eligibility (n = 37)
Excluded (n = 7)
Not meeting inclusion criteria (n = 5)
Declined to participate (n = 2)
Enrolled (n = 30)
Enrolled into treatment immediately (n = 16)
Enrolled as deferred treatment/usual care control (n = 14)
n = 6 transitioned to treatment after control phase(s)*
Treatment group
(n = 22: 16 unique + 6 post control phase)
22/22 participated in 1 semester of treatment
15/22 participated in 2 semesters of treatment
13/22 participated in 3 semesters of treatment
Deferred treatment/usual care control group
(n = 14)
14/14 participated in 1 control semester
5/14 participated in 2 control semesters
Analyzed (n = 30 unique)

Sample weekly program schedule				
Time	**Monday**	**Wednesday**	**Thursday**	**Friday**
10:00-11:00	Psychology Quiz & Lecture	Advanced Biology Quiz & Lecture	Psychology Lecture	Advanced Biology Lecture
11:00-12:00	Lecture Review	Lecture Review	Lecture Review	Lecture Review
12:00-1:00	Practice Quiz ? Review	Practice Quiz ? Review	Practice Quiz ? Review	Practice Quiz ? Review
1:00-2:00	Lunch			
2:00-3:00	Statistics	English	Statistics (Quiz)	English (Quiz)
3:00-4:00	Technology	Individual Therapy	Technology	Individual Therapy

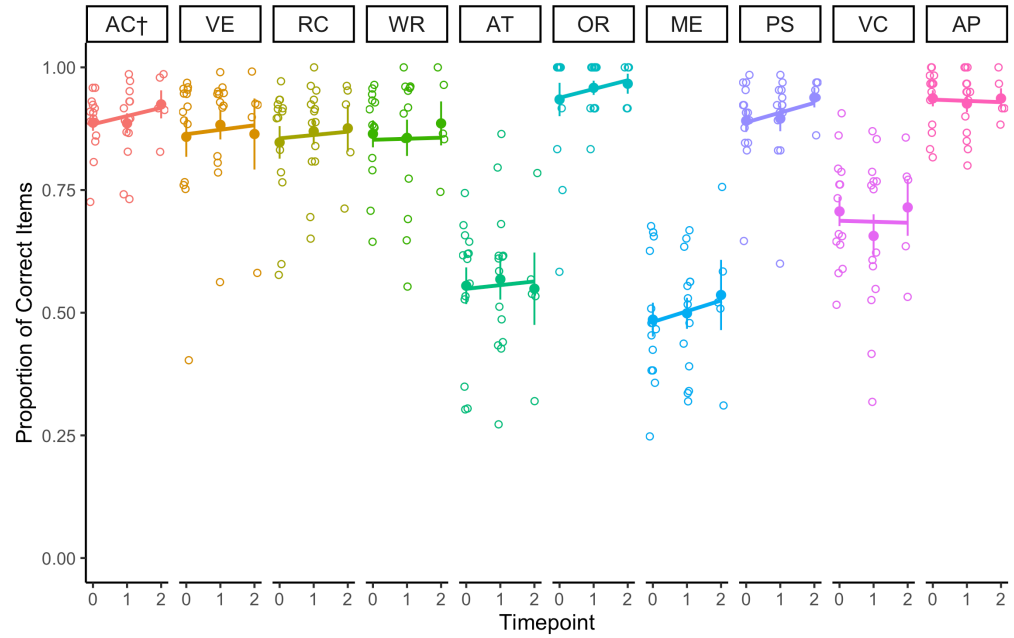
	Language				Other Cognitive					
Standardized Assessment	**Auditory Comp.**	**Verbal Expression**	**Reading Comp.**	**Written Expression**	**Attention**	**Orientation**	**Memory**	**Problem Solving**	**Visuospatial/ Constructional**	**Apraxia**
WAB-R	Auditory Comp	Spontaneous Speech, Repetition, Object Naming, Word Fluency, Sentence Completion, Responsive Speech	Reading	Writing				Calculation, Raven's Coloured Progressive Matrices	Block Design, Drawing	Apraxia
RBANS Update		Picture Naming, Semantic Fluency			Digit Span, Coding		Immediate Memory, Delayed Memory		Visuospatial/ Constructional	
SCCAN	Speech Comp.	Repetition, Naming, Connected Speech & Problem Solving	Reading	Writing	Attention		Immediate Recall, Delayed Recall	Numeric Problem Solving, Visual Problem Solving Connected Speech & Problem Solving Attention Reading		
DCT	Auditory Comp.		Reading Comp.			Orientation				
Item N	**144**	**82**	**106**	**28**	**12**	**12**	**119**	**65**	**31**	**20**
Total possible points	**253**	**293**	**151**	**132**	**108**	**12**	**141**	**77**	**79**	**60**


Overall effect of treatment by group
Proportion of Correct Items
1.00
0.75
0.50
0.25
0.00
0
1
2
Timepoint
Control
Treatment

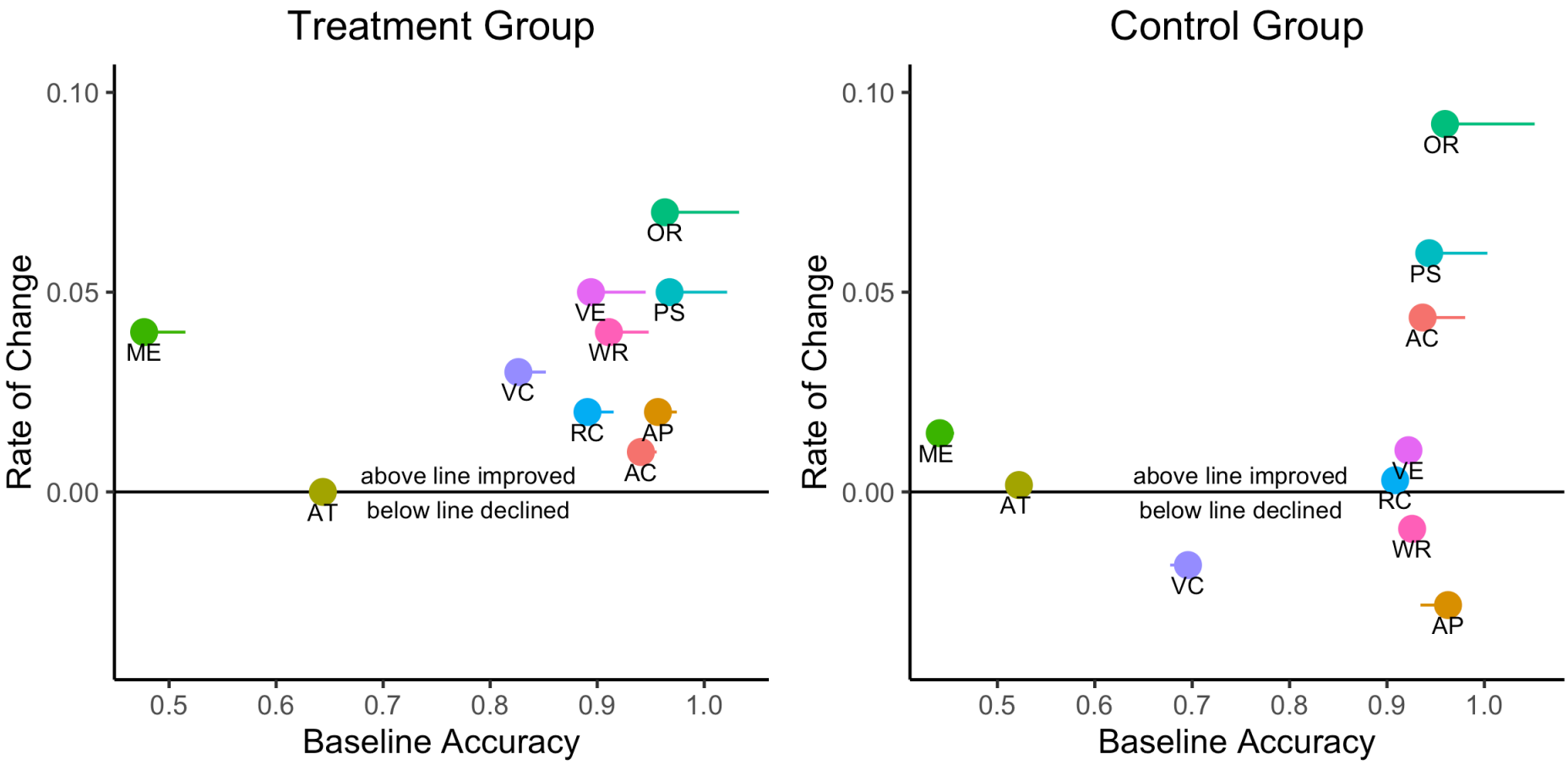
a


Timepoint effect by sub-domain for treatment group
AC
VE***
RC†
WR**
AT
OR
ME***
PS**
VC
AP
Proportion of Correct Items
1.00
0.75
0.50
0.25
0.00
0 1 2 3
Timepoint

b


Timepoint effect by sub-domain for control group
AC†
VE
RC
WR
AT
OR
ME
PS
VC
AP
Proportion of Correct Items
1.00
0.75
0.50
0.25
0.00
0 1 2
Timepoint

Baseline Accuracy vs. Rate of Change



Key: Horizontal line = predicted improvement in accuracy after one semester based on the slope estimate

Supplemental Section 1. Details regarding deferred treatment/usual care participants

Participant	Distinction within control group	Activities during control phase
C1	DT	No outpatient speech therapy
C2	UC	Outpatient speech therapy
C3	UC	Outpatient speech therapy
C4	DT	Part-time work as a baker
C5	DT	Part-time work serving food in hospital
C6	UC	Outpatient speech therapy, volunteering at the hospital
C7	UC	Outpatient speech therapy
C8	DT	Server at a restaurant
C9	UC	Outpatient speech therapy
C10	DT	Part-time work at a grocery store
C11	UC	Outpatient brain injury group therapy, volunteering at the library
C12	UC	Outpatient brain injury group once/week, part-time work at the grocery store
C13	UC	Outpatient speech therapy
C14	UC	Outpatient speech therapy

Note. UC = usual care (i.e., participants who attended outpatient speech therapy in the community during their time in the control group), DT = deferred treatment (i.e., participants who did not attend outpatient speech therapy in the community during their time in the control group). Five participants deferred treatment during the control phase, while nine participants attended usual care during the control phase.

Supplemental Section 2.

Subtest scores for standardized assessment battery

Treatment participants

	Language													Other Cognitive									
	WAB-R (out of 100%)						RBANS (M = 100, SD = 15)	SCCAN (out of 100%)			DCT (out of 100%)			WAB-R (out of 100%)		RBANS (M = 100, SD = 15)				SCCAN (out of 100%)			
	SS	AVC	REP	NWF	READ	WRITE	LANG	OE	SP	RC	WR	LIST	READ	AP	CVC	IM	VC	ATT	DM	OR	ME	AT	PS
P1	90	72	84	73	82	78	40	42	77	83	71	58	70	93	88	49	62	40	48	100	37	50	39
P2	75	78	79	87	73	54	82	79	69	83	57	68	83	87	79	69	72	40	94	100	42	75	87
P3	55	84	34	66	46	38	44	53	77	83	57	80	65	73	63	44	66	40	40	92	32	81	65
P4	50	81	79	50	44	45	40	42	62	42	57	53	60	93	80	44	69	43	44	58	42	44	48
P5	25	97	90	76	76	69	47	47	85	58	86	50	45	85	77	44	66	53	40	58	21	44	57
P6	20	54	0	0	19	28	40	16	31	67	43	0	0	58	88	40	96	43	40	50	21	50	48
P7	90	100	98	91	100	88	74	84	100	100	100	78	93	98	95	90	84	82	83	100	68	94	100
P8	100	100	91	93	100	88	82	100	92	92	86	60	75	98	93	53	78	82	44	100	53	75	74
P9	70	70	58	70	79	54	40	53	62	83	57	58	63	95	87	49	72	40	77	100	53	75	91
P10	90	88	78	92	92	74	85	89	77	92	57	90	80	92	84	57	69	43	44	100	68	88	83
P11	85	100	95	88	100	79	74	84	92	92	86	65	75	85	83	65	60	68	44	75	42	81	96
P12	90	98	97	86	63	72	57	68	85	58	57	70	40	98	63	57	72	53	40	83	47	44	61
P13*	85	100	98	86	84	89	74	95	100	100	86	63	73	95	85	61	69	64	44	92	47	94	91
P14*	85	100	98	98	100	84	104	89	100	83	86	83	90	95	91	81	69	60	88	100	58	75	87
P15	100	100	96	99	100	98	80	95	100	100	100	73	75	97	94	85	86	116	40	100	58	94	87
P16	100	97	98	91	100	98	78	95	92	100	86	70	83	98	91	78	87	56	74	92	68	81	96
P17*	90	100	92	98	100	94	92	95	100	92	86	78	80	100	93	40	72	60	40	100	84	94	96
P18*	55	85	62	86	67	51	74	58	77	75	43	63	65	85		61	64	40	74	92	63	63	61
P19*	55	75	52	68	55	58	44	32	77	100	57	58	75	93		40	66	40	44	92	47	81	78
P20	70	70	60	58	53	66	40	32	69	50	57	65	65	87	85	44	72	40	44	83	16	44	43
P21	90	100	98	97	100	100	80	95	92	92	100	73	73	97	94	85	72	77	40	100	53	81	83
P22*	95	100	100	95	100	99	64	95	100	100	71	80	85	95	96	73	84	79	40	100	68	94	91

Mean	76	88	79	79	79	73	65	70	83	83	72	65	69	91	85	60	73	57	53	89	50	73	75
SD	23	14	26	22	24	21	20	26	17	18	18	18	20	10	9	17	9	20	19	15	17	19	19
R	20 – 100	54 – 100	0 – 100	0 – 99	19 – 100	28 – 100	40 – 104	16 – 100	31 – 100	42 – 100	43 – 100	0 – 90	0 – 93	58 – 100	63 – 96	40 – 90	60 – 96	40 – 116	40 – 94	50 – 100	16 – 84	44 – 94	39 – 100

Deferred Treatment/Usual Care Control Participants

	Language													Other Cognitive								
	WAB-R (out of 100%)						RBANS (M = 100, SD = 15)	SCCAN (out of 100%)			DCT (out of 100%)			WAB-R (out of 100%)		RBANS (M = 100, SD = 15)				SCCAN (out of 100%)			
	SS	AVC	REP	NWF	READ	WRITE	LANG	OE	SP	RC	WR	LIST	READ	AP	CVC	IM	VC	ATT	DM	OR	ME	ATT	PS
C1	85	99	94	94	96	80	74	100	100	75	71	80	78	100	72	69	60	56	44	100	32	63	70
C2*	55	81	52	82	60	41	47	63	77	50	43	63	45	87	80	44	72	40	44	83	53	44	57
C3	60	80	85	76	100	85	78	63	77	58	57	80	93	93	97	73	69	53	83	100	63	81	78
C4	85	99	64	89	86	79	87	89	77	83	57	95	65	98	97	73	84	49	94	100	58	88	96
C5	100	100	100	98	98	87	87	89	85	83	86	83	83	93		73	60	53	44	100	21	81	87
C6	100	93	74	93	100	86	85	89	92	100	57	78	80	98		40	84	64	52	100	47	88	91
C7*	90	100	100	93	100	86	74	100	92	100	86	70	73	100	92	78	60	56	44	83	47	69	96
C8	95	100	98	100	100	100	92	100	100	100	86	73	93	98	95	78	78	88	83	100	89	100	100
C9	60	84	76	82	72	54	54	47	69	83	57	88	73	83		53	69	40	77	92	32	56	70
C10*	95	100	95	97	100	92	82	89	100	92	57	85	83	97	94	69	64	79	80	100	74	88	96
C11*	90	99	97	87	100	100	54	95	85	100	71	60	83	98	86	78	84	64	40	100	42	88	87
C12*	95	99	96	98	100	73	101	89	100	100	86	65	78	97		73	66	60	40	100	63	88	91
C13*	45	60	32	37	47	61	40	26	54	92	57	73	58	82		40	78	40	44	58	42	63	74
C14	80	84	86	91	85	89	74	89	92	100	71	65	70	95		49	69	68	44	100	26	81	91
Mean	81	91	82	87	89	79	74	81	86	87	67	75	75	94	89	64	71	58	58	94	49	77	84
SD	18	12	21	16	17	17	18	22	14	16	14	10	13	6	9	15	9	14	20	12	19	16	13
R	45 – 100	60 – 100	32 – 100	37 – 100	47 – 100	41 – 100	40 – 101	26 – 100	54 – 100	50 – 100	43 – 86	60 – 95	45 – 93	82 – 100	72 – 97	40 – 78	60 – 84	40 – 88	40 – 94	58 – 100	21 – 89	44 – 100	57 – 100

Note. WAB-R = Western Aphasia Battery- Revised, RBANS = Repeatable Battery for Assessment of Neuropsychological Status Index Scores, SCCAN = Scales of Cognitive and Communicative Ability for Neurorehabilitation, DCT = Discourse Comprehension Test; SS = Spontaneous Speech, AVC = Auditory Verbal Comprehension, REP = Repetition, NWF = Naming and Word Finding, READ = Reading, WRITE = Writing, OE = Oral Expression, SP = Speech Comprehension, RC = Reading Comprehension, WR = Written Expression, LIST = Listening version, READ = Reading version, AP = Apraxia, CVC = Constructional, Visuospatial and Calculation, IM = immediate memory, VC = Visuospatial/Constructional, ATT = Attention, DM = Delayed Memory, OR = Orientation, ME = Memory, PS = _Problem solving

* = Participant started as a deferred treatment/usual care control and transitioned to treatment group

Supplemental Section 3. Item assignment process when an item's subtest name did not clearly match one of the ten subdomains

For two of the standardized assessments (i.e., WAB, SCCAN), subtest names for some of the items did not clearly match one of the ten subdomains used in the present study. Those items were assigned to a subdomain based on review of neuropsychological assessment reference materials (Lezak, Howieson, and Loring 2012) and clinical judgment.

The WAB Constructional, Visuospatial, and Calculation subtest, includes the following tasks: Drawing (i.e., draw to dictation), Block Design (i.e., recreate patterns shown in a picture using colored blocks), Calculation (i.e., addition, subtraction, multiplication, division give four choices), and the Raven's Coloured Progressive Matrices (RCPM; identify the missing piece from a geometric design given six choices). This WAB subtest name and the names of the included tasks do not clearly match the subdomains used in the present study. Based on the neuropsychological assessment literature, items from the drawing (i.e., measures constructional ability; Lezak, Howieson, and Loring 2012) and the block design task (i.e., measures constructional and visuospatial function; Lezak, Howieson, and Loring 2012) were assigned to the visuospatial/constructional domain. The calculation task (i.e., assesses concept formation and reasoning (executive functions); Lezak, Howieson, and Loring 2012) and the RCPM (i.e., evaluates concept formation; Lezak, Howieson, and Loring 2012) were assigned to the problem solving domain.

Based on the SCCAN's construction, some items may contribute to more than one of the eight scale scores (i.e., oral expression, orientation, memory, speech comprehension, reading comprehension, writing, attention, problem solving). In most

cases, the name of the assessment section clearly reflected the primary nature of the item and it was used to assign the item to a subdomain. When that was not the case, the most appropriate scale option was used to assign it to a subdomain. More specifically, for SCCAN Part E. Connected Speech and Problem Solving, items 37 through 44 contributed to the oral expression scale score; however, items 38 through 43 also contributed to the problem solving scale score. For SCCAN Part G. Attention, items 48, 49, and 51 through 54 contributed to the attention scale score, but items 48 through 54 also contributed to the problem solving scale score. For SCCAN Part J. Reading, item 70 contributed to the reading, attention, and problem solving scale scores. The assignment process and associated rationale for each of these items is represented in the tables below.

Item assignment to subdomain for SCCAN Part E. Connected Speech and Problem Solving

Item #	Activity	Applicable scales based on SCCAN	Assigned Subdomain in the present study	Rationale
37.	Try to sing “Happy Birthday”	OE	VE	None needed, SCCAN scale clearly matched subdomain
38.	Now count to 5	OE, PS	VE	Measures speech production at the word level (i.e., automatic utterance)
39.	What types of accidents that could happen in a kitchen?	OE, PS	PS	Assesses concrete problem solving
40.	Now I am going to ask you to describe some things. Try to use complete sentences. a) How are a lake and an ocean similar?, b) How are a lake and an ocean different?	OE, PS	PS	Evaluates basic reasoning
41.	Tell me what a shoe is.	OE, PS	VE	Measures language production and semantic knowledge at the sentence level
42.	Tell what’s happening in this picture.	OE, PS	VE	Assesses language production at the discourse level (i.e.,

				picture description)
43.	Tell me everything you need to do to mail a letter. Start with I get a pen and paper I sit down and write	OE, PS	VE	Evaluates language production at the discourse level (i.e., procedural narrative)
44.	Syntax: If responses to items 40-43 are produced with grammatically correct sentences and normal syntactic structures (inclusion of verbs, inflections, and functors), score 1 point; otherwise, a score of 0 should be given.	OE	VE	None needed, SCCAN scale clearly matched subdomain

Note. OE = Oral Expression, PS = Problem Solving, VE = Verbal Expression (synonymous with Oral Expression using the SCCAN's naming convention)

Item assignment to subdomain for SCCAN Part G. Attention

Item #	Activity	Applicable scales based on SCCAN	Assigned Subdomain in the present study	Rationale
48.	Here's a map of the United States. Where is Florida?	AT, PS	AT	Measures simple visual scanning/attention
49.	Here's a map of the United States. Where is Oregon?	AT, PS	AT	Measures simple visual scanning/attention
50.	What time does the clock say?	PS	PS	None needed, SCCAN scale clearly matched subdomain
51.	Here's a phone. Imagine you were alone at home and there was an emergency. Who would you call? Show me.	AT, PS	PS	Assesses basic problem solving
52.	Look at these pictures. Circle all the roosters and underline all the dogs. Make sure you look at each line.	AT, PS	AT	Requires visual scanning/attention
53.	Draw a picture of a clock that shows the time 10 after 11. Include all the numbers in your drawing.	AT, PS	PS	Requires organization, planning – core executive function skills

54.	Imagine that you have won a trip to Paris. Here is a map of Paris that shows the museums and the landmarks. Where is the Eiffel Tower? Find the Eiffel Tower on the map. Trace out a route from the museum to the Eiffel Tower.	AT, PS	PS	Taxes inhibition control (i.e., suppress distractor items) Requires planning a direct route, which also involves suppressing irrelevant information (i.e., many roads to get to Eiffel Tower)

Note. AT = Attention, PS = Problem Solving

Item assignment to subdomain for SCCAN Part J. Reading

Item #	Activity	Applicable scales based on SCCAN	Assigned Subdomain in the present study	Rationale
70.	Here are your day's activities: You are meeting a friend for a late lunch at 2:00 to celebrate her birthday. You need to go to the bank to cash a check so you will have some spending money for the day. You have an appointment scheduled from 12:30-1:30. You already have a card, but you still need at least an hour to buy a present. Order the activities so that everything gets done by 2:00.	RD, AT, PS	PS	Requires making decisions based on constraints to order the activities accurately Measures planning, organization, time management, which are core executive function (problem solving) skills

Note. RD = Reading, AT = Attention, PS = Problem Solving

Supplemental Section 4. Between-group analyses

Full results of two-way interaction model between timepoint*subdomain accounting for group

Model syntax: cbind(points scored, points missed) ~ timepoint *(subdomain+group) + etiology + (timepoint | participant) +(1 | item)

Term		Log odds (SE)	Probability	z-value	Significance level	**Random effects: Variance(SD)** Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept		0.22 (0.45)	0.55	0.49	N.S.	0.91 (0.95)	2.04 (1.43)	0.01 (0.11); -0.24
Timepoint		-0.08 (0.04)	0.48	-1.92	.055			
SubDomain	Auditory Comprehension	2.36 (0.40)	0.91	5.86	***			
	Verbal Expression	1.83 (0.42)	0.86	4.40	***			
	Reading Comprehension	1.81 (0.41)	0.86	4.45	***			
	Written Expression	2.00 (0.47)	0.88	4.25	***			
	Orientation	2.83 (0.58)	0.94	4.90	***			
	Memory	-0.54 (0.40)	0.37	-1.32	N.S.			
	Problem Solving	2.84 (0.58)	0.94	4.90	***			
	Visuospatial/Constructional	0.80 (0.46)	0.69	1.74	.08			
	Upper Limb/Facial/Instrumental Apraxia	2.72(0.50)	0.94	5.41	***			
Group		0.19(0.04)	0.55	4.73	***			
Etiology		-0.08(0.34)	0.48	-0.230	N.S.			
Timepoint-by-Group		0.096(0.04)	0.52	2.69	**			

Timepoint-by-SubDomain interaction	Auditory Comprehension	0.06(0.03)	0.51	1.92	.05
	Verbal Expression	0.17(0.03)	0.54	6.03	***
	Reading Comprehension	0.05 (0.03)	0.51	1.70	.09
	Written Expression	0.10 (0.03)	0.52	2.99	**
	Orientation	0.28 (0.14)	0.57	2.00	*
	Memory	0.15 (0.03)	0.54	5.05	***
	Problem Solving	0.23 (0.14)	0.56	4.27	***
	Visuospatial/Constructional	0.13 (0.04)	0.53	3.58	***
	Upper Limb/Facial/Instrumental Apraxia	0.04 (0.56)	0.51	0.784	N.S.

Note. Timepoint was coded as a numeric predictor: Group was dummy-coded with control as the reference level. Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Etiology (i.e., TBI, non-TBI) was dummy-coded with non-TBI as the reference level. SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Full results of three-way interaction model between timepoint*subdomain*group

cbind(obs_score, (poss_score - obs_score)) ~ timepoint_num * SubDomain * Group + ET + (1 + timepoint_num | ID) + (1 |domainitem)

Term		Log odds (SE)	Probability	z-value	Significance level	**Random effects: Variance (SD)** Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept		0.14(0.46)	0.53	0.31	N.S.	0.91 (0.95)	2.05 (1.43)	0.01(0.11); -0.22
Timepoint		-0.10 (0.06)	0.48	-0.16	***			
Etiology		-0.08 (0.34)	0.48	-0.24	N.S.			
Group		0.30 (0.08)	0.57	4.00	***			
SubDomain	Auditory Comprehension	2.39(0.41)	0.92	5.82	***			
	Verbal Expression	2.01(0.42)	0.88	4.75	***			
	Reading Comprehension	2.07 (0.42)	0.89	4.95	***			
	Written Expression	2.20 (0.48)	0.90	4.56	***			
	Orientation	2.87(0.62)	0.95	4.60	***			
	Memory	-0.49(0.41)	0.38	-1.18	N.S.			
	Problem Solving	2.75 (0.44)	0.94	6.20	***			
	Visuospatial/Constructional	0.58 (0.47)	0.64	1.24	N.S.			
	Apraxia	2.84 (0.52)	0.94	5.44	***			
Timepoint-by-	Auditory Comprehension	0.17 (0.08)	0.54	2.16	*			

SubDomain interaction	Verbal Expression	0.04 (0.7)	0.51	0.53	N.S.
	Reading Comprehension	0.01 (0.08)	0.50	0.08	N.S.
	Written Expression	-0.04(0.09)	0.49	-0.51	N.S.
	Orientation	0.37(0.35)	0.59	1.06	N.S.
	Memory	0.05(0.07)	0.51	0.74	N.S.
	Problem Solving	0.26(0.13)	0.56	1.96	*
	Visuospatial/Constructional	-0.08(0.09)	0.48	-0.94	N.S.
	Upper Limb/Facial/Instrumental Apraxia	-0.11(0.14)	0.47	-0.80	N.S.
Timepoint-by-Group		0.01 (0.07)	0.50	0.12	N.S.
	Auditory Comprehension	-0.08 (0.10)	0.48	-0.87	N.S.
	Verbal Expression	-0.27 (0.09)	0.43	-3.05	**
	Reading Comprehension	-0.40 (0.10)	0.40	-3.90	***
	Written Expression	-0.28(0.11)	0.43	-2.58	**
SubDomain -by-Group	Orientation	-0.08 (0.37)	0.48	-0.22	N.S.
	Memory	-0.06(0.09)	0.49	-0.62	N.S.
	Problem Solving	0.13 (0.15)	0.53	0.87	N.S.
	Visuospatial/Constructional	0.44 (0.110	0.61	3.96	***
	Upper Limb/Facial/Instrumental Apraxia	-0.17(0.17)	0.46	-0.97	N.S.

Timepoint-by-SubDomain-by-Group	Auditory Comprehension	-0.11(0.09)	0.47	-1.25	N.S.
	Verbal Expression	0.18 (0.08)	0.54	2.31	*
	Reading Comprehension	0.10 (0.09)	0.52	1.08	N.S.
	Written Expression	0.19 (0.10)	0.55	2.04	*
	Orientation	-0.10 (0.38)	0.48	-0.26	N.S.
	Memory	0.11 (0.08)	0.53	1.37	N.S.
	Problem Solving	-0.05(0.14)	0.49	-0.32	N.S.
	Visuospatial/Constructional	0.18(0.10)	0.54	1.86	N.S.
	Upper Limb/Facial/Instrumental Apraxia	0.19 (0.16)	0.55	1.24	N.S.

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Group was dummy-coded with control as the reference level. Etiology was dummy-coded (i.e., TBI and non-TBI with non-TBI as the reference level). SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Full results of three-way interaction model between timepoint*group*etiology

cbind(obs_score, (poss_score - obs_score)) ~ timepoint_num * Group*ET + (1 + timepoint_num | ID) + (1 |domainitem)					**Random effects: Variance (SD)**		
Term	Log odds (SE)	Probability	z-value	Significance level	Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept	1.94 (0.27)	0.87	7.30	$p < .001$	0.97 (0.99)	3.48 (1.87)	0.10 (0.10); -0.31
Timepoint	-0.01 (0.05)	0.50	-0.18	N.S.			
Group	0.05 (0.05)	0.51	0.93	N.S.			
Etiology	-0.40 (0.36)	0.40	-1.11	N.S.			
Timepoint-by-Group	0.13 (0.05)	0.53	2.52	$p < .011$			
Timepoint-by-Etiology	0.11 (0.07)	0.53	1.65	.098			
Group-by-Etiology	0.40 (0.08)	0.60	4.86	$p < .001$			
Timepoint-by-Group-by-Etiology	-0.11 (0.07)	0.47	-1.50	N.S.			

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Group was dummy-coded with control as the reference level. Etiology was dummy-coded (i.e., TBI and non-TBI with non-TBI as the reference level). SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Code for extracting domain-specific intercepts and slopes for the between-group GLMMs

These contrast matrices were developed based off of methods previously used for conducting multiple pairwise comparisons for categorical predictors (Mirman, 2013, 2014). Each column in the matrices below (created using the "rbind" function in base R) refers to an estimate from the generalized linear mixed effects model, in this case the between group subdomain model with intercepts and slopes (BG 3). Each row reflects the contrast comparison that is being tested. The "1" and "0" values reflect the weight being assigned to each element of the contrast.

For the domain-specific intercept estimates, a "1" is in the group column and a "1" is in the subdomain*group interaction column for the domain of interest (e.g., auditory comprehension). Otherwise, all the other elements are "0." The intercept reflects the estimate of attention (i.e., subdomain reference level) for the experimental group. The subdomain*group interaction column reflects the interaction estimate for the subdomain of interest (e.g., auditory comprehension) relative to attention in the experimental group relative to the control group (group reference level). Combining them while canceling out other terms in the model provides the intercept for the subdomain of interest in the experimental relative to the control group (e.g., baseline auditory comprehension in the experimental group versus the control group).

For the domain-specific slope estimates, "1" is in the timepoint*group estimate column and a "1" is in the subdomain of interest* timepoint*group interaction column. Otherwise, all the other elements are "0." The timepoint*group column reflects the estimate of attention (subdomain reference level) over time for the experimental group

relative to the control group (group reference level). The subdomain of interest*timepoint*group interaction column reflects the interaction estimate for the subdomain of interest relative to the attention subdomain for the experimental group relative to the control group over time. Combining them while canceling out other terms in the model provides the slope for the subdomain of interest in the experimental group relative to the control group (e.g., auditory comprehension in the experimental group versus the control group over time).

Domain-specific intercept contrast matrix

```
contrast.matrix.intercept.group<-rbind(
 `E vs C_AC` =c (rep(0,times=11), 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_AP` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_ME` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_OR` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_PS` =c (rep(0,times=11), 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_RC` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_VC` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_VE` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_WR` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),
 `E vs C_AT` =c (rep(0,times=11),1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0))
```

Key: AC = auditory comprehension, AP = apraxia, ME = memory, OR = orientation, PS = problem solving, RC = reading comprehension, VC = visuospatial/constructional, VE = verbal expression, WR = written expression

Code to extract the domain-specific intercepts

```
summary(glht(m_subdomain_group, contrast.matrix.intercept.group))
```

Domain-specific slope contrast matrix

```
contrast.matrix.slope.group<-rbind(
  `E vs C_AC`       = c(rep(0, times=22), 1, rep(0, times=9), 1, 0, 0, 0, 0, 0, 0, 0, 0),
  `E vs C_AP`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 1, 0, 0, 0, 0, 0, 0, 0),
  `E vs C_ME`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 1, 0, 0, 0, 0, 0, 0),
  `E vs C_OR`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 1, 0, 0, 0, 0, 0),
  `E vs C_PS`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 1, 0, 0, 0, 0),
  `E vs C_RC`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 0, 1, 0, 0, 0),
  `E vs C_VC`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 0, 0, 1, 0, 0),
  `E vs C_VE`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 0, 0, 0, 1, 0),
  `E vs C_WR`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 0, 0, 0, 0, 1),
  `E vs C_AT`       = c(rep(0, times=22), 1, rep(0, times=9), 0, 0, 0, 0, 0, 0, 0, 0, 0))
```

Code to extract the domain-specific intercepts

```
summary(glht(m_subdomain_group, contrast.matrix.slope.group))
```

Key: AC = auditory comprehension, AP = apraxia, ME = memory, OR = orientation, PS = problem solving, RC = reading comprehension, VC = visuospatial/constructional, VE = verbal expression, WR = written expression

Supplemental Section 5. Within-group analyses
Within-group analyses for the deferred treatment/usual care control group

Full results of subdomain-intercepts only model for the treatment group

Model syntax: cbind(obs_score, (poss_score - obs_score)) ~ Timepoint + SubDomain + Etiology + (1 + Timepoint | ID) + (1 | Item)

Term		Log odds (SE)	Probability	z-value	Significance level	**Random effects: Variance(SD)** Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept		0.43 (0.49)	0.61	0.88	N.S.	0.93 (0.97)	2.11 (1.45)	0.01 (0.10); -0.42
Timepoint		0.12 (0.02)	0.53	5.04	***			
Etiology	TBI	-0.48 (0.38)	0.38	-1.27	N.S.			
SubDomain	Auditory Comprehension	2.27 (0.43)	0.91	5.31	***			
	Verbal Expression	1.80 (0.44)	0.86	4.08	***			
	Reading Comprehension	1.64 (0.43)	0.84	3.80	***			
	Written Expression	1.93 (0.50)	0.87	3.89	***			
	Orientation	2.99 (0.60)	0.95	4.95	***			
	Memory	-0.48 (0.43)	0.38	-1.12	N.S.			
	Problem Solving	3.06 (0.45)	0.96	6.76	***			
	Visuospatial/Constructional	1.11 (0.48)	0.75	2.29	*			
	Upper Limb/Facial/Instrumental Apraxia	2.61 (0.53)	0.93	4.96	***			

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Etiology (i.e., TBI, non-TBI) was dummy-coded with non-TBI as the reference level. SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Full results of subdomain- intercepts and slope model for treatment group

Model syntax: glmer(cbind(obs_score,(poss_score-obs_score)) ~ Timepoint* SubDomain + Etiology + (1+Timepoint | ID) + (1 | Item)						Random effects: Variance (SD)		
Term		Log odds (SE)	Probability	z-value	Significance level	Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept		0.59 (0.48)	0.64	1.23	N.S.	0.92 (0.96)	2.11 (1.45)	0.01 (0.09); -0.37
Timepoint		-0.01 (0.03)	0.50	-0.31	N.S.			
Etiology	TBI	-0.49 (0.39)	0.38	-1.25	NS.			
SubDomain	Auditory Comprehension	2.17 (0.42)	0.90	5.16	***			
	Verbal Expression	1.54 (0.43)	0.82	3.56	***			
	Reading Comprehension	1.51 (0.43)	0.82	3.53	***			
	Written Expression	1.73 (0.49)	0.85	3.54	***			
	Orientation	2.68 (0.61)	0.94	4.41	***			
	Memory	-0.68 (0.42)	0.34	-1.62	N.S.			
	Problem Solving	2.81 (0.45)	0.94	6.24	***			
	Visuospatial/Constructional	0.97 (0.48)	0.73	2.02	*			
	Upper Limb/Facial/Instrumental Apraxia	2.51 (0.52)	0.92	4.81	***			
Timepoint-by-SubDomain interaction	Auditory Comprehension	0.07 (0.03)	0.52	2.00	*			
	Verbal Expression	0.22 (0.03)	0.55	6.81	***			
	Reading Comprehension	0.11 (0.04)	0.53	2.99	**			

Written Expression	0.16 (0.04)	0.54	4.06	***
Orientation	0.29 (0.15)	0.57	1.92	.05
Memory	0.17 (0.03)	0.54	4.98	***
Problem Solving	0.23 (0.06)	0.56	3.78	***
Visuospatial/Constructional	0.11 (0.04)	0.53	2.69	**
Upper Limb/Facial/Instrumental Apraxia	0.08 (0.06)	0.52	1.30	N.S.

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Etiology was dummy-coded (i.e., TBI and non-TBI with non-TBI as the reference level). SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Within-group analyses for the deferred treatment/usual care control group

Full results of subdomain-intercepts only model for control group

Model syntax: cbind(obs_score, (poss_score - obs_score)) ~ Timepoint + SubDomain + Etiology + (1 + Timepoint | ID) + (1 | Item)

Term		Log odds (SE)	Probability	z-value	Significance level	**Random effects: Variance(SD)** Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
Intercept		0.09 (0.50)	0.52	0.18	N.S.	0.64 (0.80)	1.91 (1.38)	0.03 (0.17); -0.56
Timepoint		0.01 (0.07)	0.50	0.09	N.S.			
Etiology	TBI	0.36(0.39)	0.59	0.91	N.S.			
SubDomain	Auditory Comprehension	0.17 (0.08)	0.54	2.10	*			
	Verbal Expression	0.03 (0.07)	0.51	0.50	N.S.			
	Reading Comprehension	0.005 (0.08)	0.50	0.06	N.S.			
	Written Expression	-0.04 (0.09)	0.49	-0.51	N.S.			
	Orientation	0.37 (0.35)	0.59	1.05	N.S.			
	Memory	0.05 (0.07)	0.51	0.72	N.S.			
	Problem Solving	0.23 (0.13)	0.56	1.85	.064			
	Visuospatial/Constructional	-0.08 (0.09)	0.48	-0.93	N.S.			
	Upper Limb/Facial/Instrumental Apraxia	-0.12 (0.14)	0.47	-0.84	N.S.			

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Etiology (i.e., TBI, non-TBI) was dummy-coded with non-TBI as the reference level. SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Full results of subdomain- intercepts and slope model for control group

Model syntax: glmer(cbind(obs_score,(poss_score-obs_score)) ~ Timepoint* SubDomain + Etiology + (1+Timepoint | ID) + (1 | Item)						Random effects: Variance (SD)		
Term		Log odds (SE)	Probability	z-value	Significance level	Intercept: ID	Intercept: Item	Slope: Time-by-ID; Corr
						0.64 (0.80)	1.91 (1.38)	0.03 (0.17) ; -0.54
Intercept		0.09 (0.50)		0.18	N.S.			
Timepoint		0.01 (0.07)		0.09	N.S.			
Etiology	TBI	0.36 (0.39)		0.91	N.S.			
SubDomain	Auditory Comprehension	2.61 (0.43)		6.03	***			
	Verbal Expression	2.38 (0.44)		5.38	***			
	Reading Comprehension	2.21 (0.44)		5.03	***			
	Written Expression	2.44 (0.51)		4.82	***			
	Orientation	3.08 (0.65)		4.72	***			
	Memory	-0.33 (0.43)		-0.76	N.S.			
	Problem Solving	2.72 (0.46)		5.92	***			
	Visuospatial/Constructional	0.74 (0.48)		1.53	N.S.			
	Upper Limb/Facial/Instrumental Apraxia	3.16 (0.54)		5.90	***			
Timepoint-by-	Auditory Comprehension	0.17 (0.08)		2.10	*			
	Verbal Expression	0.03 (0.07)		0.50	N.S.			

SubDomain interaction	Reading Comprehension	0.005 (0.08)	0.50	N.S.
	Written Expression	-0.04 (0.09)	-0.51	N.S.
	Orientation	0.37 (0.35)	1.05	N.S.
	Memory	0.05(0.07)	0.72	N.S.
	Problem Solving	0.23(0.13)	1.85	0.06
	Visuospatial/Constructional	-0.08 (0.09)	-0.93	N.S.
	Upper Limb/Facial/Instrumental Apraxia	-0.12 (0.14)	-0.84	N.S.

Note. Timepoint was coded as a numeric predictor: Pre-treatment = “0”; Post-treatment 1 = “1”, Post-treatment 2 = “2”, Post-treatment 3 = “3.” Etiology was dummy-coded (i.e., TBI and non-TBI with non-TBI as the reference level). SubDomain was dummy-coded with Attention as the reference level. The correlation value refers to the strength of association between the random slope of timepoint and the random intercept of participant. The negative value reflects participants with lower baseline accuracy have steeper slopes.

Code for extracting domain-specific intercepts and slopes for the within-group GLMMs

These contrast matrices were developed based off of methods previously used for conducting multiple pairwise comparisons for categorical predictors (Mirman, 2013, 2014). Each column in the matrices below (created using the "rbind" function in base R) refers to an estimate from the generalized linear mixed effects model, in this case the subdomain model with intercepts and slopes (WG3). Each row reflects the contrast comparison that is being tested. The "1" and "0" values reflect the weight being assigned to each element of the contrast.

For the domain-specific intercept estimates, a "1" is in the intercept column and a "1" is in the subdomain of interest column (e.g., auditory comprehension). Otherwise, all the other elements are "0." The intercept reflects the estimate for the reference level in subdomain, in this case, attention. The subdomain of interest column reflects the estimate for that subdomain relative to the reference level, attention. Combining them while canceling out other terms in the model provides the intercept value for the subdomain of interest alone (e.g., baseline accuracy for auditory comprehension).

For the domain-specific slope estimates, "1" is in the timepoint estimate column and a "1" is in the subdomain of interest-by-timepoint interaction column. Otherwise, all the other elements are "0." The timepoint column reflects the estimate for the reference level over time, in this case attention. The subdomain of interest-by-timepoint interaction column reflects the estimate for that subdomain relative to the reference level, attention, over time (e.g., auditory comprehension compared to attention over time). Combining

them while canceling out other terms in the model provides the slope value for the subdomain of interest alone (e.g., rate of change for auditory comprehension).

Domain-specific intercept contrast matrix

```
contrast.matrix.intercept <- rbind(
  `AC`        =c(1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `AP`        =c(1,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `ME`        =c(1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `OR`        =c(1,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `PS`        =c(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `RC`        =c(1,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `VC`        =c(1,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0),
  `VE`        =c(1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0),
  `WR`        =c(1,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0))
```

Key: AC = auditory comprehension, AP = apraxia, ME = memory, OR = orientation, PS = problem solving, RC = reading comprehension, VC = visuospatial/constructional, VE = verbal expression, WR = written expression

Code to extract the domain-specific intercepts

```
summary(glht(m_subdomain, contrast.matrix.intercept))
```

Domain-specific slope contrast matrix

```
contrast.matrix.slope <- rbind(
`timepoint:AC`      =c(0,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0),
`timepoint:AP`      =c(0,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0),
`timepoint:ME`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0),
`timepoint:OR`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0),
`timepoint:PS`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0),
`timepoint:RC`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0),
`timepoint:VC`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0),
`timepoint:VE`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0),
`timepoint:WR`      =c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0))
```

Code to extract the domain-specific intercepts

```
summary(glht(m_subdomain, contrast.matrix.slope))
```

Key: AC = auditory comprehension, AP = apraxia, ME = memory, OR = orientation, PS = problem solving, RC = reading comprehension, VC = visuospatial/constructional, VE = verbal expression, WR = written expression