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Cognition, Self-Awareness, and Driving after Moderate-to-Severe Traumatic Brain Injury

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COGNITION, SELF-AWARENESS, AND DRIVING AFTER MODERATE-TO-SEVERE TRAUMATIC BRAIN INJURY

by

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COGNITION, SELF-AWARENESS, AND DRIVING AFTER MODERATE-TO-SEVERE TRAUMATIC BRAIN INJURY

CHRISTINA A. DIBLASIO

MEDICAL/CLINICAL PSYCHOLOGY

ABSTRACT

Moderate-to-severe traumatic brain injury (TBI) often results in cognitive deficits in learning/memory, executive functions, and self-awareness. Cognitive impairments and unawareness of those impairments hinder driving capacity, yet a large proportion of survivors return to driving after injury. Given that many survivors are driving, it is essential to understand how cognition and self-awareness impact driving practices. To date, studies in this area are limited. This dissertation aimed to (1) create a normative sample for the Brief Test of Adult Cognition by Telephone (BTACT), a short cognitive battery adapted for telephone administration and validated for the TBI population; (2) examine the relationship between cognitive function (memory and executive function) and return to driving after TBI; (3) examine the influence of cognition and self-awareness on driving patterns (frequency and restriction) following TBI.

Normative data for the BTACT were derived from a national sample of 6,747 English-speaking healthy adults aged 23–84 years (aim 1). For aims two and three, participants were 585 adults with moderate-to-severe TBI enrolled in the TBI Model System multi-center program. Cross-sectional driving and cognitive outcomes were collected via structured interview and telephone-administered cognitive battery (BTACT) across the recovery trajectory, ranging from 1–30 years after injury. Cognitive impairment was defined as z score $\leq$ -1.0, and participants were classified as having impaired self-awareness when there was objective cognitive impairment but no self-reported cognitive impairment.

The BTACT normative data were created based on age, sex, and education. Memory and executive function impacted return to driving after TBI, but these effects washed out when family income and motor function were taken into account. Thirty-nine percent of survivors had impaired self-awareness. The majority drove numerous times weekly, but survivors were not driving in all situations. Survivors with more cognitive impairment were more likely to have impaired self-awareness and also restricted their driving more.

Driving after moderate-to-severe TBI is multifaceted. Survivors with memory and executive function impairments, lower income, and less motor function are at greater risk for not driving after injury. Among those who return to driving, most survivors drive frequently but the situations they drive in differ based on their cognition.

Keywords: *adult; traumatic brain injury; driving; cognition; self-awareness; rehabilitation*

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LIST OF ABBREVIATIONS

BTACT	Brief Test of Adult Cognition by Telephone
TBI	traumatic brain injury

INTRODUCTION

Traumatic Brain Injury and Lasting Burden

Traumatic brain injury (TBI) is a sudden injury to the brain caused by an external force, with injuries ranging from mild, moderate, to severe alterations in brain function. More than 2.8 million Americans sustain a TBI each year (Centers for Disease Control and Prevention, 2019b). Moderate-to-severe TBI is a chronic health condition and leading cause of permanent disability in the United States, often due to cognitive deficits from the injury (Centers for Disease Control and Prevention, 2015; Corrigan & Hammond, 2013). An estimated 5.3 million individuals in the United States are living with a TBI-related disability, resulting in roughly $76 billion in societal economic burden (Centers for Disease Control and Prevention, 2015; Coronado, 2012). Moderate-to-severe TBIs, which require hospitalization, account for approximately 90% of that cost (Centers for Disease Control and Prevention, 2019a). The tremendous burden placed on survivors, family, and the community make moderate-to-severe brain injuries a necessary focus.

Return to Driving After Traumatic Brain Injury

Driving a vehicle is an integral activity of daily living for most adults in the United States. TBI often hinders one’s ability to safely operate a vehicle (Schultheis & Whipple, 2014), resulting in a large proportion of survivors who do not drive after injury (Rapport, Hanks, & Bryer, 2006). In a longitudinal study, only 53% of survivors returned to driving

5 years after moderate-to-severe TBI (Novack et al., 2010). In a recent cross-sectional study examining driving 1–30 years post-injury, only 67% of survivors were driving at the time of interview (Novack et al., 2021). *Driving cessation is one of the most functionally debilitating and burdensome consequences of TBI*. Inability to drive after TBI is related to worse outcomes and greater disability, including loss of independence, less community integration, diminished participation in productive roles like employment, poor life satisfaction and quality of life, fewer social relationships, greater emotional disturbance, and reduced access to basic needs (Erler et al., 2018; Fleming, Liddle, Nalder, Weir, & Cornwell, 2014; McKerral, Moreno, Delhomme, & Gelinas, 2019; Novack et al., 2010; Rapport, Bryer, & Hanks, 2008; Schultheis & Whipple, 2014). Consequently, more burden is placed on the survivor, caregiver, family-unit, and community. Return to driving is a major step in recovery by enabling independence, reintegration in the community, and greater access to activities and productive roles (Erler et al., 2018; Fleming et al., 2014; McKerral et al., 2019). Thus, promoting return to driving is a critical area to focus research and rehabilitation efforts to reduce burden.

Return to driving following TBI is a predominant goal for survivors and caregivers, but often a challenge to achieve. First, the decision to return to driving following TBI is complex since the benefits of burden reduction must outweigh potential risks to safety. Second, state regulations on driving after TBI vary widely, with many states imposing no legal restrictions (Schultheis & Whipple, 2014). Additionally, professional consultation on return to driving after brain injury is often lacking (Rapport et al., 2006). Consequently, the decision to drive after TBI is largely left to the survivor and caregiver (Novack et al., 2010). Caregivers often play a major role and may restrict the survivor's driving due cautious concerns about safety risks, lack of information from medical professionals, and lack of an on-road driving test (Coleman et al., 2002; Rapport et al., 2006). Lastly, residual medical problems (e.g., seizures) and financial limitations (e.g., inability to afford vehicle and insurance expenses) after TBI create barriers to return to driving (Novack et al., 2021; Rapport et al., 2006). Survivors may have the capacity for driving but barriers may prevent driving resumption, resulting in detrimental consequences to community participation, independence, and life satisfaction. Examining return to driving, while accounting for these influential factors (i.e., seizures, income), is needed to improve understanding of the current state of driving practices following TBI. Such information may be used to support the need for policy changes and recovery services.

Cognitive Deficits Impact Driving

Moderate-to-severe TBI causes brain dysfunction, often leaving survivors with non-reversible and lasting cognitive deficits (Centers for Disease Control and Prevention, 2015, 2019b). Impairments in attention, learning, memory, problem solving, and self-awareness are highly prevalent after moderate-to-severe TBI (Dikmen et al., 2009; Ham et al., 2014; Kelley et al., 2014; Prigatano & Sherer, 2020). Residual cognitive deficits are extremely debilitating, as they create a cascade of daily living challenges, functional limitations, and often prevent survivors from returning to their pre-injury activities and roles (Centers for Disease Control and Prevention, 2015). Specifically, cognitive deficits from TBI hinder the survivor’s ability to drive a vehicle following injury (Coleman et al., 2002; Hawley, 2001; Lundqvist, Alinder, & Rönnberg, 2008).

Memory

Memory involves the ability to learn and recall new information. Following moderate-to-severe TBI, impairments in memory are common and have been identified up to 20 years post-injury (Dikmen, Temkin, McLean, Wyler, & Machamer, 1987; Dikmen et al., 2009; Draper & Ponsford, 2008; Hoofien, Gilboa, Vakil, & Donovick, 2001; Millis et al., 2001; Sigurdardottir et al., 2015). Memory deficits negatively impact individuals' ability to learn from their environment and use prior experiences to inform their behavior in the present. Specific to driving, memory impairments raise concerns about the capacity to effectively navigate to destinations, including recalling where one is going, why they are going there, and routes to effectively navigate there.

Executive Function

Executive functions are higher-order, complex cognitive skills that allow individuals to plan, focus their attention, monitor and regulate their behavior, make quick decisions, and problem solve when unanticipated challenges arise. Following moderate-to-severe TBI, impairments in executive function are prevalent and have been identified up to 10 years post-injury (Dikmen et al., 2009; Draper & Ponsford, 2008; Finnanger et al., 2013; Sigurdardottir et al., 2015). Executive function skills are needed to make decisions about driving (e.g., what route to take, what time of day) and to adapt to changes during a drive (e.g., traffic, weather) (Fleming et al., 2014). These skills have been found to impact fitness to drive and driving safety (via traffic violations) after TBI (Coleman et al., 2002).

Overall, a better understanding of how specific cognitive functions impact driving practices after TBI is needed. Greater information about the impact memory and executive function have on return to driving and driving practices may be incorporated in clinical care to provide tailored education to survivors and caregivers as well as support the need for intervention development.

Lack of Self-Awareness Impairs Daily Function

Impaired self-awareness from brain injury reflects disturbances in subjective experience and reduced insight into one’s own condition, whereby the survivor is not aware that the injury caused significant changes to their functioning (Chiou, Carlson, Arnett, Cosentino, & Hillary, 2011; Flashman & McAllister, 2002; Prigatano, 2005). Impaired self-awareness is common following moderate-to-severe TBI, as 20–50% of survivors exhibit self-awareness impairments 6+ months post-injury with impairments shown up to 5 years post-injury (Bivona et al., 2019; Geytenbeek, Fleming, Doig, & Ownsworth, 2017; Kelley et al., 2014; Prigatano & Sherer, 2020). Self-awareness is important for utilization of strategies to compensate for deficits (Geytenbeek et al., 2017; Kelley et al., 2014; Lundqvist & Alinder, 2007). If survivors are aware of their impairments, then they may develop compensatory strategies to minimize the detrimental effects of impairments on their daily functioning. Without awareness of impairments, compensatory strategies will not be used (Lundqvist & Alinder, 2007). Thus, unawareness of deficits puts survivors at a higher risk for unsafe behaviors and poor treatment adherence (Merchán-Baeza, Rodriguez-Bailon, Ricchetti, Navarro-Egido, & Funes, 2020). In general, impaired self-awareness is related to worse outcomes, including reduced independent living skills, employment, and social functioning (Geytenbeek et al., 2017; Hurst, Ownsworth, Beadle, Shum, & Fleming, 2020; Ownsworth & Clare, 2006).

Impaired self-awareness of cognitive abilities is prevalent and often more severe than impaired awareness of more basic abilities (e.g., self-care skills) (Flashman & McAllister, 2002; Hart, Sherer, Whyte, Polansky, & Novack, 2004; Hurst et al., 2020). If survivors underestimate their cognitive limitations, then they are less likely to adjust their behavior accordingly to compensate for those limitations. Given the cognitive demands that come with driving, poor self-awareness of cognitive deficits raises concerns about return to driving decisions and highlights the need to consider the role of self-awareness on driving post-injury (Ham et al., 2014; Kelley et al., 2014; Prigatano & Sherer, 2020). Following injury, survivors may resume driving without medical consultation because they perceive themselves as cognitively intact and able to drive. Additionally, self-awareness is necessary to self-monitor driving behavior and develop compensatory strategies that promote safe driving (Geytenbeek et al., 2017; Lundqvist & Alinder, 2007; Pachana & Petriwskyj, 2006). Limited self-awareness likely results in poor awareness of cognitive abilities necessary for driving and may impact whether an individual engages in self-regulatory behavior, including limiting the frequency of their driving and avoiding challenging or potentially dangerous situations (e.g., rush-hour). Prior studies found that impaired self-awareness negatively impacted driving ability (e.g., more adverse driving incidents and failed on-road driving evaluation) (Gooden et al., 2017; Rapport et al., 2008; Schanke & Sundet, 2000). Taken together, cognitive deficits and unawareness of those deficits raise concerns about driving safety and potential risk to self and other drivers. A greater understanding of the impact of self-awareness on driving practices is important to guide services that promote return to driving post-TBI, such as supporting the need to incorporate self-awareness assessment in cognitive evaluations and clinical driving evaluations as well as the need for education services and rehabilitation programs that address impaired self-awareness post TBI.

Gaps in the Current Literature

In summary, the literature supports that cognitive impairments from TBI create a cascade of daily living challenges for survivors and often prevent them from returning to their premorbid activities and roles, including driving a motor vehicle. Cessation of driving is one of the most functionally debilitating consequences of TBI, as driving is integral to independence, access to basic needs, and life satisfaction. Cognitive impairments and unawareness of those impairments that result from TBI are barriers to returning to driving, and subsequently regaining independence, community integration, and productive roles.

There are numerous gaps in the current literature on cognition and driving after moderate-to-severe TBI. To date, studies in this area have been limited by small sample sizes, mixed causes of brain disorder, variable duration of follow-up, and have largely investigated fitness to drive after injury (e.g., on-road driving performance). Given that survivors of TBI may be actively driving (without formal evaluation of their fitness to drive), it is essential to examine survivors' driving patterns after injury. Along that line, there is sparse research examining how specific cognitive functions impact survivors' driving patterns after injury. Greater information is needed about the impact of memory and executive function on return to driving and driving practices. Additionally, research looking at the role of self-awareness on driving after TBI is sparse and has primarily examined on-road driving performance, rather than driving patterns in daily life. A greater understanding is needed about the impact of cognitive function and the impact of self-awareness on driving behaviors after TBI.

No known study has examined whether pre-injury driving experience serves a protective role. Driving becomes an overlearned, automatic behavior with experience, which is less vulnerable to impaired frontal lobe brain function than non-routine activities (Lezak, Howieson, Bigler, & Tranel, 2012). Research suggests that individuals with more long-term driving experience may rely on procedural knowledge to a greater extent than novice drivers (Lundqvist et al., 2008). Therefore, longer driving experience may benefit return to driving post injury (Lundqvist et al., 2008), but this has not been scientifically examined yet. Examining factors that influence return to driving post TBI and the potential effect of pre-injury driving experience will provide important information on the underlying protective mechanisms that buffer the impact of injury, as well as inform future research investigating predictors of driving outcomes.

Lastly, the literature on cognitive function post-TBI is predominantly limited to studies that required participants to complete cognitive testing in person, which raises concerns about sample and attrition biases. Telehealth-based cognitive assessment (Munro Cullum, Hynan, Grosch, Parikh, & Weiner, 2014) is relatively new, with only recent widespread use due to the COVID-19 pandemic. Telehealth services may promote greater access and utilization of cognitive testing in underserved populations (Caze, Dorsman, Carlew, Diaz, & Bailey, 2020). Research supports the positive relationship between (even brief) cognitive testing and return to driving outcomes post TBI, as well as the usefulness of cognitive testing in routine driving assessment (Coleman et al., 2002; Lundqvist et al., 2008; Palubiski & Crizzle, 2016). For TBI survivors who have not returned to driving, telehealth cognitive testing provides an alternative that eliminates the primary barrier of transportation to the testing site. Thus, removing this barrier may allow for samples that are more representative of the overall TBI population.

The Present Study

This dissertation consists of three papers that help address these important gaps as well as contribute greater understanding about the impact of cognitive function and self-awareness of deficits on driving a motor vehicle after TBI. Of note, this was the first study to utilize validated, telephone-administered cognitive testing to examine the impact of cognition on return to driving following TBI. By eliminating in-person testing barriers (e.g., transportation to the testing site), the findings of this study may be more representative of the overall TBI population compared to prior studies of cognition and return to driving.

The first paper aimed to create a normative sample for the Brief Test of Adult Cognition by Telephone (BTACT) (Tun & Lachman, 2006), a short cognitive battery adapted for telephone administration and validated for the TBI population (DiBlasio, Novack, Cook, Dams-O'Connor, & Kennedy, 2021; Lachman, Agrigoroaei, Tun, & Weaver, 2014; Tun & Lachman, 2006). Hypotheses were that BTACT normative data would be derived to estimate the composite means with a standard deviation less than 1.0. It was also hypothesized that BTACT scores would decrease with age and increase with education. The BTACT was subsequently used in the remaining two papers as a measure of cognitive function with standardization of participants' test scores based on the normative sample of healthy adults.

The second paper examined the relationship between cognitive function (memory and executive function) and return to driving after moderate-to-severe TBI. It was hypothesized that better cognitive function would be associated with higher odds of active driving status post-injury, such that individuals with higher BTACT scores would be more likely to be driving. Furthermore, it was also hypothesized that the relationship between cognitive function and post-injury driving status would be moderated by pre-injury driving experience (years), such that pre-injury driving experience would serve a protective function and buffer the impact of impaired cognition to increase the odds of active driving status post-injury. This was the first known study to investigate whether pre-injury driving experience served a protective role, which has important implications for promoting return to driving post injury.

The third paper examined the influence of cognition and self-awareness on driving patterns (frequency and restriction) following moderate-to-severe TBI. Hypotheses were that better cognitive function would be directly related to more frequent and less restricted driving after TBI. In addition, it was hypothesized that self-awareness would partially mediate the relationships between (1) cognition and driving frequency and (2) cognition and restricted driving behavior following moderate-to-severe TBI.

RESEARCH LETTER: PERFORMANCE OF THE BRIEF TEST OF ADULT COGNITION BY TELEPHONE IN A NATIONAL SAMPLE

by

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ABSTRACT

Objective: To create a larger, more representative community comparison sample of the Brief Test of Adult Cognition by Telephone (BTACT) data to facilitate assessment of cognitive function in research studies. **Setting:** National US community-based survey. **Participants:** In total, 6747 healthy adults aged 23 to 84 years (53% female; mean age = 55 years, SD = 13). **Design:** Secondary data analysis of BTACT data collected from the National Survey of Midlife Development in the United States (MIDUS) II and MIDUS Refresher cohorts. **Main Measures:** The BTACT, a brief (15-20 minute) measure of global cognitive function validated for telephone administration. **Results:** This article provides BTACT community comparison sample data based on age, sex, and education from a national sample. Similar to other cognitive measures, BTACT scores decreased with age and increased with education. **Conclusions:** The BTACT community comparison sample will facilitate investigation of cognitive functioning in large-scale traumatic brain injury research studies and will support secondary analysis of existing BTACT data gathered through the MIDUS study.

Key words: *adult, traumatic brain injury, cognition, data analysis, neuropsychology, rehabilitation, telephone*

INTRODUCTION

Assessment of cognitive abilities is essential in research tracking recovery following moderate-severe traumatic brain injury (TBI). Traditional neuropsychological testing is time- and labor-intensive and typically must be administered in person, which may be impractical in some research situations. Telephone-based cognitive assessment has the advantages of lower cost and greater feasibility, although it cannot completely replace traditional testing.

The Brief Test of Adult Cognition by Telephone (BTACT)[1] is a short in-person or telephone-administered battery of tests that assesses key aspects of cognitive functioning (i.e., episodic verbal memory, working memory, verbal fluency, inductive reasoning, and processing speed). It was designed for use in the National Survey of Midlife Development in the United States (MIDUS) by adapting established neuropsychological tests and supplementing with new subtests.[2,3] It has been shown to be a valid measure of cognition for healthy adults across a wide range of ages and ability levels.[1,4] In the context of TBI, the BTACT was shown to be a feasible and efficient measure of cognition for individuals who sustained moderate-severe TBI.[5] Additionally, the BTACT composite scores of overall cognition, verbal memory, and executive function were found to be valid measures in a TBI inpatient population. ("Convergent Validity of In-Person Assessment of Inpatients with Traumatic Brain Injury Using the Brief Test of Adult Cognition by Telephone (BTACT)" submitted as companion paper to this issue of the *Journal of Head Trauma Rehabilitation*)

Given that the BTACT is brief (15-20 minutes) and validated for telephone administration in TBI, it has the potential to be a useful measure of cognitive function for longitudinal research focusing on recovery after TBI.[5] The BTACT has been adopted for use in several TBI studies, including the TBI Model Systems program, Translating Research and Clinical Knowledge in TBI, and the Chronic Effects of Neurotrauma Consortium. It is therefore important to ensure an appropriate community comparison sample is available to establish the baseline distribution of the reference population and facilitate calculation of standardized scores. Ideally, to accurately interpret performance of a research sample, community reference data should be collected from a large sample whose demographic characteristics are representative of individuals whose performance will be measured with the test. It is further important to establish standardized scoring methods for the BTACT so that scores can be compared across cohorts and studies. Previous work has compared BTACT data from different MIDUS cohorts, but no study has combined the cohorts to create a sample with an expanded age range that includes younger adults under 32 years (MIDUS Refresher) and older adults over 76 years (MIDUS II).[6] Accordingly, this manuscript details methods used to pool BTACT data collected from the MIDUS II and MIDUS Refresher cohorts to create a larger, more representative community comparison sample for research use, while also illustrating standardized scoring practices for use across studies.

METHODS

Study Sample

Available community data for the BTACT come from the MIDUS II study cohort and the MIDUS Refresher cohort. The MIDUS study is a national, longitudinal study of health and well-being during adulthood in a probability sample of Americans.[2] The first wave of the MIDUS study (MIDUS I)[7] collected survey data by telephone on 7,108 participants in 1995–1996 based on random digit dialing of phone numbers, with oversampling of urban dwellers, older adults, and men.[8,9] Eligible participants were non-institutionalized, English-speaking adults, aged 25 to 75, living in the continental United States. Further details about MIDUS study design are provided elsewhere (http://midus.wisc.edu).

The MIDUS II study,[10] conducted between 2004 and 2006, followed the original MIDUS I sample for an average of 9 years after initial contact, incorporating the BTACT for the first time. Of the original sample, 4,512 participants, aged 32 to 84 years, completed the MIDUS II interview and the BTACT via telephone.[3,8] MIDUS II BTACT summary data were published by Lachman et al.[4]

The MIDUS Refresher study,[11] conducted between 2011 and 2016, supplemented the original MIDUS I sample to address attrition and permit cohort comparisons and resulted in a wider age range. The study recruited a national simple random sample of 3,577 adults aged 23 to 76 years,[6,11] of which 2,763 participants completed the BTACT.[12]

Measures

Brief Test of Adult Cognition by Telephone (BTACT)

The BTACT consists of six primary subtests, presented below in order of administration. The Stop and Go Switch Task[1] was not included in this study. Subtest scores were compiled to create three composite scores: overall cognition, episodic verbal memory, and executive function.

Word List Immediate Recall measures immediate recall of a 15-word list derived from the Rey Auditory Verbal Learning Test (RAVLT).[13] The list is read aloud to participants, who then must immediately recall the words. The score represents the total number of words recalled correctly.

Digits Backward measures working memory with Digit Span Backward from the Wechsler Adult Intelligence Scale-III.[14] A string of 2-8 numbers is read aloud and participants are asked to repeat the numbers in reverse order. The score ranges from 0-8, based on the longest set of digits correctly repeated backwards.

Category Fluency involves naming as many animals as possible in 60 seconds as a measure of executive functioning. The score is the total number of different animals named.

Number Series measures inductive reasoning by asking for a sixth number in a series of 5 presented numbers. Participants must identify the pattern in the sequence and apply that pattern to successfully determine the sixth number. The score ranges from 0-5 depending on the total number of sequences completed correctly.

Backward Counting, a measure of processing speed, requires participants to quickly generate a non-automatic sequence of familiar items by counting backwards from 100 aloud as quickly and accurately as possible, for a span of 30 seconds. The score is the total number of digits correctly produced.[6]

Word List Delayed Recall, a measure of memory retrieval, involves recall of the RAVLT word list presented approximately 15 minutes earlier. The score ranges from 0-15, based on the total number of words recalled correctly.

Procedures

The MIDUS II and Refresher raw BTACT and demographic (age, sex, and education) data were obtained from the Inter-University Consortium for Political and Social Research data archive (retrieved May 14, 2019 from https://www.icpsr.umich.edu/icpsrweb/ICPSR/series/203). Age and years of education were categorized into variables with 5 (20-30s, 40s, 50s, 60s, and 70-80s) and 2 levels (less than bachelor's degree vs bachelor's degree or higher), respectively. Means and standard deviations (SDs) were computed for each BTACT subtest by age decade, sex, and education level. Subtests were used to create 3 composite scores: BTACT Composite, Episodic Verbal Memory Composite, and Executive Function Composite. First, *z*-scores were derived for each of the 6 subtests by age, sex, and education based on the stratified mean and SD of the respective MIDUS II or Refresher sample. Composites were created by averaging *z*-scores for the respective subtests and then re-standardizing (mean = 0, SD = 1) the average to generate a composite *z*-score. The overall BTACT Composite was created from all 6 subtests; the Episodic Verbal Memory Composite from Word List Immediate Recall and Word List Delayed Recall; and the Executive Function Composite from Digits Backward, Category Fluency, Number Series, and Backward Counting. Means and SDs were computed for each

BTACT composite by age decade, sex, and education level. Composites were only computed for cases with complete data on all required constituent subtests.

Data Analysis

We derived weighted means and SDs from the MIDUS II and MIDUS Refresher cognitive data by age decade, sex, and education level (see Supplemental Digital Content 1, available at: http://links.lww.com/JHTR/A422, for full description of weighted statistics calculations). Weights were proportional to the sample size in each strata derived from the MIDUS II and Refresher data. There were few individuals younger than 30 years and older than 79 years in the MIDUS II project and the MIDUS Refresher project. To adjust for the small sample sizes in these age strata, all participant information for those younger than 30 years or older than 79 years were combined with those aged between 30-39 and 70-79 years, respectively.

Differences in BTACT performance by age decade were tested using one-way analysis of variance and the Jonckheere-Terpstra test to determine trends of lower median scores with older age decades. Differences in BTACT performance by education level were tested using independent-samples *t* test.

RESULTS

This study included 4,200 participants from the MIDUS II study after excluding 312 individuals with missing education data. As documented by Lachman et al.,[4] the sample was predominantly comprised of non-Hispanic, white females who were well-educated and aged 28 to 84 (**Table 1**). From the MIDUS Refresher study, we included 2,547 after excluding 216 individuals with missing education data. The majority of this sample was comprised of non-Hispanic, white individuals aged 23 to 76 years with a bachelor's degree or higher (**Table 1**). Overall, the final community comparison sample included 6,747 English-speaking adults between the ages of 23 to 84 years (**Table 1**).

We present the means and SDs for the MIDUS II and MIDUS Refresher combined sample based on age decade, sex, and education level for each of the BTACT subtests (see **Table 2**) and composites (see **Table 3**). Higher scores indicate better performance. The scores decreased with age and increased with greater education (see Supplemental Digital Content 2, available at: http: //links.lww.com/JHTR/A423). An example of standardized scoring procedures is provided (see Supplemental Digital Content 3, available at: http://links.lww.com/ JHTR/A424), and an online application for scoring and standardizing raw BTACT data may be accessed at https://hub.tbindsc.org/tbimsdatadictionary/Home.

Table 1. Sample Characteristics.

	MIDUS II Sample (N = 4,200)	MIDUS Refresher Sample (N = 2,547)	Combined Sample (N = 6,747)
Age, mean (SD), years	56.0 (12.3)	52.58 (14.2)	54.7 (13.2)
Sex, *n* (%)			
Male	1925 (45.8)	1219 (47.9)	3144 (46.6)
Female	2275 (54.2)	1328 (52.1)	3603 (53.4)
Race, *n* (%)			
White	3741 (89.1)	2054 (80.6)	5795 (85.9)
Black/African American	126 (3.0)	134 (5.3)	260 (3.9)
Asian	21 (0.5)	34 (1.3)	55 (0.8)
American Indian/Alaska Native	30 (0.7)	18 (0.7)	48 (0.7)
Native Hawaiian/Other Pacific Islander	4 (0.1)	4 (0.2)	8 (0.1)
Multiracial	164 (3.9)	138 (5.4)	302 (4.5)
Other	97 (2.3)	155 (6.1)	252 (3.7)
Unknown	13 (0.3)	7 (0.3)	20 (0.3)
Refused	4 (0.1)	3 (0.1)	7 (0.1)
Ethnicity, *n* (%)			
Hispanic or Latino	124 (2.8)	107 (4.2)	231 (3.4)
Not Hispanic or Latino	4064 (96.8)	2435 (95.6)	6499 (96.3)
Unknown	10 (0.2)	2 (0.1)	12 (0.2)
Refused	2 (0.0)	3 (0.1)	5 (0.1)
Education, *n* (%)			
Less than high school	243 (5.8)	108 (4.2)	351 (5.2)
High school/GED	1114 (26.5)	441 (17.3)	1555 (23.0)
Some college	921 (21.9)	458 (18.0)	1379 (20.4)
Associate degree	325 (7.7)	290 (11.4)	615 (9.1)
Bachelor’s degree or higher	1597 (38.0)	1250 (49.1)	2847 (42.3)

DISCUSSION

This article provides BTACT community comparison sample data based on age, sex, and education from a national sample of 6,747 healthy adults to facilitate assessment of cognitive function in research studies. Scores decreased with age and increased with education, which is consistent with published neuropsychological norms and supports the face validity of the MIDUS community comparison sample. Reference BTACT data were standardized by age, sex, and education to allow for performance-based comparisons between a TBI sample and the MIDUS community comparison sample, adjusting for demographics. Thus, standardized BTACT scores can provide a benchmark of how the cognitive status of an individual who sustained a TBI compares to a sample of cognitively intact individuals of the same age, sex, and education. Composite scores were re-standardized to facilitate interpretation on a common metric.

The BTACT is a well-validated telephone-administered cognitive test battery, making it valuable for large-scale longitudinal research initiatives examining the trajectory of cognition over time following TBI.[5] Telephone administration may be preferred in large epidemiological studies whereby in-person visits may introduce selection bias. As demonstrated here, BTACT reference data are available from a large sample drawn from across the United States with a wide age range, which supports the stability of score estimates and their representativeness of the general population. Existing MIDUS and BTACT data may be requested for use at www.icpsr.umich.edu/web/NACDA/studies/25281 and www.icpsr.umich.edu/web/NACDA/studies/37081.

Some limitations remain; for example, there are fewer subjects in the lowest and highest age decades of the community comparison sample, so scores may be less accurate for adults in these age groups. It should be noted that the community comparison sample is predominantly white, and caution is warranted when comparing the community comparison sample to diverse populations. Finally, the BTACT is a brief cognitive assessment tool and has not been validated for clinical use or diagnosis.

Overall, our characterization of the combined BTACT community comparison sample will facilitate investigation of cognitive functioning in large scale TBI research studies, and will support secondary analysis of existing BTACT data gathered through the MIDUS study.

Table 2. Community Comparison Sample Data for the BTACT Subtests: Means and Standard Deviations Based on Age Decade, Sex, and Education Level.

			Age Decade														
			20-30s			40s			50s			60s			70-80s		
Measure	**Sex**	**Education**	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N
Word List Immediate Recall	Male	Less than BA	7.00	1.91	201	6.46	2.01	372	6.05	2.01	413	5.64	1.97	387	4.57	1.89	284
		BA or higher	7.68	2.01	233	7.47	1.92	342	7.09	1.97	360	6.39	1.87	335	5.60	2.21	205
	Female	Less than BA	7.59	2.36	259	7.43	2.16	452	7.26	2.20	563	6.97	2.25	519	5.61	2.15	433
		BA or higher	8.37	2.24	247	8.13	2.07	371	8.08	2.14	342	7.78	2.30	280	6.63	2.62	125
Word List Delayed Recall	Male	Less than BA	4.63	2.26	195	4.13	2.19	360	3.53	2.12	388	3.21	2.30	367	2.27	2.07	263
		BA or higher	5.46	2.27	218	5.07	2.35	331	4.48	2.24	355	3.75	2.18	327	3.17	2.46	195
	Female	Less than BA	5.70	2.72	245	5.47	2.50	427	4.97	2.61	539	4.59	2.61	497	3.11	2.45	402
		BA or higher	6.44	2.66	235	5.99	2.24	358	5.72	2.54	327	5.29	2.67	267	4.42	2.69	115
Digits Backward	Male	Less than BA	5.15	1.54	203	4.92	1.47	372	4.56	1.50	411	4.66	1.35	388	4.25	1.34	287
		BA or higher	5.88	1.45	233	5.53	1.41	342	5.28	1.49	362	5.21	1.43	332	4.79	1.60	205
	Female	Less than BA	5.09	1.53	256	5.06	1.48	450	4.94	1.50	563	4.92	1.43	519	4.51	1.66	433
		BA or higher	5.69	1.32	247	5.35	1.40	371	5.35	1.39	342	5.38	1.56	280	5.05	1.50	126
Category Fluency	Male	Less than BA	20.11	6.56	202	19.23	5.65	372	18.36	5.67	411	17.62	5.79	388	15.41	5.04	287
		BA or higher	24.71	6.18	232	22.90	5.88	342	21.90	5.84	363	20.63	6.13	334	17.22	5.79	205
	Female	Less than BA	19.84	5.80	258	18.89	5.76	450	18.10	5.65	563	16.64	5.40	519	14.61	5.27	434
		BA or higher	23.19	5.95	246	22.81	5.97	369	21.69	6.06	341	20.51	5.69	278	18.58	5.77	125

Table 2. (continued)

			Age Decade														
			20-30s			40s			50s			60s			70-80s		
Measure	**Sex**	**Education**	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N
Number Series	Male	Less than BA	2.76	1.52	201	2.25	1.51	370	2.05	1.45	408	1.84	1.35	382	1.42	1.20	281
		BA or higher	3.66	1.19	230	3.38	1.35	342	3.37	1.30	362	2.99	1.40	334	2.46	1.49	204
	Female	Less than BA	2.17	1.43	256	2.06	1.48	446	1.85	1.42	553	1.60	1.31	510	1.24	1.18	419
		BA or higher	3.16	1.37	246	3.13	1.37	370	2.91	1.35	338	2.67	1.44	275	2.21	1.39	122
Backward Counting	Male	Less than BA	43.90	12.32	200	40.89	11.43	369	37.09	10.83	408	34.57	9.62	386	29.76	8.62	285
		BA or higher	49.83	11.41	229	46.46	11.17	340	44.48	11.23	360	39.06	9.59	334	34.47	10.06	204
	Female	Less than BA	40.86	11.45	257	37.89	11.05	446	35.10	10.00	560	31.58	8.39	516	27.57	8.55	431
		BA or higher	46.03	10.93	245	43.64	9.57	369	40.00	9.34	338	36.34	9.51	277	31.38	8.27	125

Note: The community comparison sample was derived by combining the MIDUS II and MIDUS Refresher cohorts, although ages 20-30 are primarily from the MIDUS Refresher cohort and 70-80 are primarily from the MIDUS II cohort. N = combined (MIDUS II and Refresher) sample size for the corresponding level. BA = bachelor's degree.

Table 3. Community Comparison Sample Data for the BTACT Composites: Means and Standard Deviations Based on Age Decade, Sex, and Education Level.

			Age Decade														
			20-30s			40s			50s			60s			70-80s		
Measure	Sex	Education	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N
Episodic Verbal Memory Composite[a]	Male	Less than BA	0.01	0.93	195	0.02	0.92	360	0.02	0.91	388	0.01	0.93	367	0.02	0.93	263
		BA or higher	0.02	0.94	218	0.004	0.93	331	-0.001	0.92	355	0.01	0.92	327	0.02	0.95	195
	Female	Less than BA	0.01	0.95	245	0.002	0.94	427	-0.001	0.93	539	0.01	0.94	497	0.03	0.92	402
		BA or higher	0.004	0.96	234	0.01	0.92	358	0.01	0.93	327	0.01	0.92	267	-0.004	0.94	115
Executive Function Composite[b]	Male	Less than BA	0.003	0.67	200	0.004	0.72	369	0.01	0.69	406	0.02	0.70	381	0.004	0.66	281
		BA or higher	0.001	0.65	229	0.003	0.66	340	0.01	0.66	359	0.00	0.69	332	0.005	0.63	203
	Female	Less than BA	-0.002	0.65	251	0.01	0.69	445	0.01	0.66	552	0.001	0.67	507	0.02	0.66	417
		BA or higher	0.01	0.66	244	-0.001	0.67	369	0.002	0.65	338	0.02	0.63	275	0.02	0.60	122
BTACT Composite[c]	Male	Less than BA	0.01	0.66	194	0.01	0.67	359	0.03	0.64	384	0.02	0.65	363	0.02	0.62	260
		BA or higher	0.01	0.60	218	0.002	0.60	330	-0.003	0.61	353	0.001	0.61	326	0.02	0.61	193
	Female	Less than BA	0.01	0.60	238	0.02	0.63	425	0.01	0.62	533	0.01	0.63	489	0.04	0.64	391
		BA or higher	0.01	0.63	234	0.002	0.60	357	0.01	0.60	327	0.03	0.58	265	0.03	0.54	112

Note: BA = bachelor's degree. [a]The Episodic Verbal Memory Composite is the average of the z-scores for Word List Immediate Recall and Word List Delayed Recall, standardized to a z-score (M=0, SD=1). [b]The Executive Function Composite is the average of the z-scores scores for Digits Backward, Category Fluency, Number Series, and Backward Counting, then standardized to a z-score (does not include the Stop and Go Switch Task). [c]The BTACT Composite is the average of the z-scores for all six subtests, standardized to a z-score. Composites were calculated only for cases with scores on all constituent subtests.

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MEDIATORS AFFECTING THE RELATIONSHIP BETWEEN COGNITION AND DRIVING AFTER MODERATE-TO-SEVERE TRAUMATIC BRAIN INJURY

by

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ABSTRACT

Objective: Moderate-to-severe traumatic brain injury (TBI) often results in cognitive deficits that hinder the ability to drive a motor vehicle, thereby negatively impacting independence and quality of life. Unfortunately, determinants affecting the relationship between impaired cognition and return to driving have been understudied. The current study examined the relationship between cognitive function and driving status following moderate-to-severe TBI. **Participants and Methods:** Participants were 585 adults aged 19–96 years (mean = 46 years; 70% male) who sustained a moderate-to-severe TBI and were enrolled in the TBI Model System. Cross-sectional driving survey data were obtained for participants ranging 1–30 years post injury (mean = 8.2 years), including questions on current driving status. The Brief Test of Adult Cognition by Telephone (BTACT) was used to assess cognitive function (memory and executive function). The relationship between driving status (driving vs. not driving) and concurrent cognitive function was examined using hierarchical binary logistic regression, controlling for demographics (age, sex, race, education), injury characteristics (time since injury, injury severity, seizure history in past year), and medical/social factors (family income, motor function, urban-rural classification). Follow up univariate analyses (independent-samples t test, one-way analysis of variance, linear regression) were conducted to examine the influence of each significant covariate on cognition as the outcome. **Results:** Seventy percent of the sample were driving at the time of interview. Better memory (OR = 1.36, $p < .05$) and executive function (OR = 1.38, $p < .001$) significantly predicted active driving status. However, the relationships between cognition and driving status were not significant when the covariates were added to the model (memory: OR = 1.24, $p = .09$; executive function: OR = 1.10, $p = .38$). Greater family income, better motor function, and absence of seizure were significantly related to active driving status (all $p < .05$). Additionally, family income and motor function were significantly related to memory and executive function (all $p < .001$), while history of seizure was not significant. **Conclusion:** The findings indicate that memory and executive function are significantly associated with driving status following TBI, but these relationships diminish in significance with inclusion of sociodemographic/medical factors, particularly family income and motor function. Memory, executive function, income, and motor function may be important factors to target for future research and development of intervention services to guide return to driving decisions.

Keywords: *brain injuries; neurocognition; driving*

INTRODUCTION

Moderate-to-severe traumatic brain injury (TBI) often results in cognitive impairments that negatively impact everyday functioning and prevent survivors from participating in their pre-injury activities,[1] including driving a vehicle. Return to driving is a predominant goal for many survivors of TBI, but often a challenge to achieve. Studies have shown that between 20-60% of survivors do *not* drive after their TBI,[2-6] with estimates often improving with more time after injury. Inability to drive after TBI leads to significantly worse outcomes, including reduced access to basic needs, loss of independence, diminished participation in productive roles (e.g., employment), poor life satisfaction, less participation in social activities, decreased emotional well-being, and less community involvement.[4-9] Given the debilitating and burdensome consequences of driving cessation, it is crucial to better understand factors that influence whether or not a survivor drives a vehicle after their TBI.

The decision to return to driving is complex and multifaceted. TBI often hinders one's ability to safely operate a vehicle.[9] Thus, the benefits of burden reduction must outweigh potential risks to safety. State regulations on driving after TBI vary widely, with many states imposing no legal restrictions,[9] and professional guidance on fitness to return to driving is often lacking.[9,10] Caregivers frequently play a major role in the decision and may restrict the survivor's driving due to concerns about safety and lack of a formal clinical driving assessment or guidance from healthcare providers.[3,6,10] On the other hand, cognitive obstacles to driving may be less recognized by patients and caregivers, so survivors may return to driving on the basis of their physical readiness with less consideration of their cognitive readiness.[11] Further complicating the decision, residual medical problems (e.g., seizures, motor impairments, orthopedic injuries) and financial limitations (e.g., insurance cost) after TBI create barriers to return to driving.[2,10] These sociodemographic and medical factors may prevent driving resumption, resulting in detrimental consequences to community participation, independence, and life satisfaction. Therefore, it is necessary to assess driving status after TBI within the context of these factors to better understand the current state and multidimensionality of return to driving among survivors of TBI.

While there are a number of factors that impact return to driving after TBI, cognitive dysfunction is among the most influential barriers. Residual cognitive deficits from moderate-to-severe TBI may significantly hinder the survivor's ability to drive a vehicle following injury.[3,12,13] Specifically, diminished attention, processing speed, visual memory, and executive function abilities have been associated with reduced on-road driving performance.[14-17] However, the current literature is limited by small sample sizes and has largely investigated cognitive fitness to drive following injury via on-road and off-road driving assessments. Given formal driving evaluations are often lacking post-injury, survivors of TBI may be actively driving, even though they would be deemed unfit to drive on a formal driving assessment. Additionally, prior studies have shown that survivors of TBI often drive despite the presence of problems that could significantly impact safe driving and recommendations not to drive..[11,12] Therefore, research is needed examining what specific cognitive abilities influence whether or not a survivor is driving in their day-to-day life. This knowledge will help to inform the development of guidelines for return to driving decisions that rehabilitation professionals could use in discussions with survivors and caregivers when navigating this important topic.

Memory and executive function impairments are common following moderate-to-severe TBI[18-24] and important to consider for return to driving a vehicle. Memory impairments raise concerns about the capacity to recall where one is going, why they are going there, and the routes to effectively navigate there. Executive function deficits negatively impact an individual's ability to plan ahead, effectively manage problems that arise, make quick decisions, use good judgment, and flexibly adjust their behavior to meet the demands of a situation. These skills are needed to make decisions about driving (e.g., what route to take, what time of day) and to adapt to changes during a drive (e.g., traffic, weather).[3,8] Additionally, pre-injury driving experience is relevant, as it may serve a protective role and buffer the impact of injury on return to driving. Research suggests that individuals with more long-term driving experience may rely on procedural knowledge to a greater extent than more novice drivers when operating a vehicle.[13] Given that overlearned behaviors are less vulnerable to frontal lobe damage than non-routine activities,[25] longer driving experience may benefit an individual in returning to drive post-TBI.[13]

The present study aimed to investigate the role of cognitive function (memory and executive function) on driving status following moderate-to-severe TBI. Additionally, this is the first known study to investigate whether pre-injury driving experience serves a protective role. A better understanding of the impact of cognition and other intervening factors associated with driving will help guide rehabilitation services that promote return to driving, and subsequently increase community integration and independence.

METHODS

Participants

The present study involved secondary, cross-sectional analysis of participants who sustained a moderate-to-severe TBI and were enrolled in the Traumatic Brain Injury Model System (TBIMS) across eight centers in the United States (i.e., in Alabama, Virginia, Pennsylvania, New Jersey, Michigan, Minnesota, Colorado, and Washington). The TBIMS is a multi-center national program funded by the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR) to support longitudinal research on outcomes after TBI. At enrollment, all participants were at least 16 years of age, sustained a moderate-to-severe TBI, received medical care in a TBIMS-affiliated acute care hospital within 72 hours of injury, and were admitted to an affiliated comprehensive rehabilitation facility following discharge from acute care. Diagnosis of moderate-to-severe TBI was defined by at least one of the following criteria: Glasgow Coma Scale (GCS) score < 13 on emergency department admission, loss of consciousness > 30 minutes, post-traumatic amnesia > 24 hours, or trauma-related intracranial abnormality on neuroimaging. Informed consent for participation was obtained directly from the injured person or a legally authorized representative. Participants were excluded if they never drove a vehicle (n = 20) or did not complete any cognitive testing (n = 18). Additionally, seventeen participants who self-identified as a race other than white or Black were excluded due to small sample sizes.

Procedures

The TBIMS telephone follow-up interviews occurred at 1, 2, and 5 years after injury and every 5 years thereafter. The standard TBIMS interview included questions on demographics, injury characteristics, and cognitive function. After completing the standard follow-up interview, participants consented to complete a driving survey. The driving survey took an additional 15-20 minutes and was completed by phone or mail. All TBIMS participants who were eligible for a follow-up interview from May 1, 2018 to May 31, 2019 were provided the option to complete the driving survey. Cross-sectional driving data were obtained for participants across the recovery trajectory, extending from 1-30 years post-injury (median = 5 years, interquartile range = 13 years).

Measures

Cognitive Function

Participants were administered the *Brief Test of Adult Cognition by Telephone* (BTACT)[26] during the standard TBIMS interview. The BTACT is a brief telephone-administered cognitive test battery shown to be a feasible and valid measure of cognitive function among individuals with TBI.[27-29] The BTACT was comprised of six subtests that were combined to create three composite scores. The *Episodic Verbal Memory Composite* was created from two subtests adapted from the Rey Auditory Verbal Learning Test that measure word list learning and delayed recall.[30] The *Executive Function Composite* was derived from the remaining four subtests that measure: 1) working memory via digit span backward from the Wechsler Adult Intelligence Scale-III,[31] 2) processing speed via timed backwards counting,[32] 3) semantic verbal fluency via animal fluency,[33] and 4) reasoning via number sequencing pattern completion.[26] The *BTACT Composite* was created from all six subtests as measure of overall cognitive status.

Driving Status Outcome

As part of the driving survey, participants were asked, '*Are you driving a car, truck, or motorcycle now?*' Two groups were formed based on their responses: 1) individuals who reported they were driving at the time of the interview (active drivers) and 2) individuals who indicated they were not driving at the time of the interview (non-drivers). Further details on the driving survey were provided by Novack et al.[2]

Pre-Injury Driving Experience

Pre-injury driving experience was defined as the number of years participants drove prior to their injury. Participants were asked, '*Did you drive a car, truck or motorcycle before your TBI?*', and, '*At what age did you start driving*?' Using this data and age at injury (obtained from the standard TBIMS interview), the number of years participants drove prior to injury was calculated.

Covariates

Sociodemographic factors. Age at interview, sex assigned at birth (male, female), self-identified race (white, Black), education (less than bachelor's degree, bachelor's degree or higher), urban-rural classification based on zip code (rural, suburban, urban), and family income (in thousands, < 25, 25-49.9, 50-99.9, 100+) were collected by self-report during the standard TBIMS interview. The vast majority of individuals self-identified as white (70.6%) and Black (26.6%), thus individuals who self-identified as a race other than white or Black (2.8%) were excluded due to small sample sizes for meaningful analysis.

Medical factors. TBI severity was measured using time to follow commands (TFC, in days), which was obtained during hospitalization following injury as part of the standard TBIMS data collection protocol. Time since injury (in years) and history of seizure in the year prior to the interview (yes/no) were collected during the interview.

Participants completed the *Functional Independence Measure* (FIM)[34] as part of the standard TBIMS follow-up interview. The FIM is a measure of disability in carrying out activities of daily living. The FIM Motor[35] subscale was comprised of 13 items assessing how much assistance a person needs to complete daily activities that require physical function: eating, grooming, bathing, dressing the upper body, dressing the lower body, toileting, bladder management, bowel management, transfers to bed / chair / wheelchair, transfers to toilet, transfers to tub/shower, locomotion (walking or wheelchair propulsion), and stair climbing. Participants rated how much assistance they needed to do each activity from 1-7, with 1 indicating total assistance and 7 indicating complete independence. The FIM Motor total score ranged from 13 to 91, with higher scores representing greater independence in physical function. The FIM Motor total score was used in the present study as a measure of motor function.

Sensitivity Analysis

As anxiety may affect return to driving, a sensitivity analysis was conducted using the *General Anxiety Disorder Scale–7* (GAD-7),[36] a 7-item validated screening measure for generalized anxiety disorder.[36] Completed as part of the standard TBIMS follow-up interview, participants rated how often they experienced seven defining symptoms of GAD over the last two weeks from 0-3, with 0 indicating ‘not at all’ and 3 indicating ‘nearly every day.’ The GAD-7 total score for the seven items ranged from 0 to 21, with higher scores indicating more anxiety symptoms.

Data Analysis

For the cognitive data, thirty-four participants were unable to complete the entire BTACT cognitive battery due to cognitive reasons (i.e., their BTACT Composite score was derived from data with scores assigned on at least one subtest; n=14 were missing one subtest, n=1 missing two subtests, and n=19 missing all six subtests). Thus, following recommended BTACT scoring methods,[37] subtest raw scores of 0 were assigned for those individuals (as such, these scores were not counted as missing data). Among individuals with assigned BTACT scores of 0, nineteen were driving at the time of interview. The BTACT raw data were standardized to z scores by age decade, sex, and education.[37] For participants aged 19 years (n=5) and 90-96 years (n=4), community comparison sample data[37] from the 20-30s age decade and the 70-80s age decade were used, respectively.

Multiple data imputation was completed to account for incomplete data across variables and significant differences between participants with complete and incomplete data. Ten imputation iterations were conducted using fully condition specification imputation method through IBM SPSS 28 Missing Values statistical software.

Demographic differences between active drivers and non-drivers were calculated using independent-samples *t* test for continuous variables and binary logistic regression for categorical variables. For annual household family income, each contrast was compared to the reference category of less than $25,000/year.

Binomial logistic regression was used to test if verbal memory (BTACT Episodic Verbal Memory Composite z-score) and executive function (BTACT Executive Function Composite z-score) were related to driving status (driving vs. not driving). Demographics (age, sex, race, education), injury characteristics (time since injury, injury severity, history of seizure in past year), and medical/social factors (family income, motor function, urban-rural classification) shown to be related to cognition and driving post-TBI were included in the model as covariates. Holm corrections were used to protect against inflation of Type I error.[38] It was hypothesized that better cognitive function would be associated with greater odds of active driving status post-injury. To determine if the findings were consistent across varying points in recovery, logistic regression analyses were repeated with an interaction term for time since injury to examine the relationship between cognitive function and driving status at specific years post-injury (i.e., 1 year, 2 years, 5 years, and 10+ years post-injury). For covariates that were significant predictors of driving status, univariate follow-up ANOVA, independent-samples t test, and linear regression analyses were conducted to examine the relationship of each covariate to each cognitive domain.

Additionally, moderation analysis was used to determine if pre-injury driving experience (i.e., number of years an individual drove prior to their injury) served a protective role in buffering the impact of impaired cognition (via BTACT Composite) to increase the odds of active driving status post-injury. Pre-injury driving years and the interaction term between pre-injury driving years and overall cognitive status were added to the model to test the moderation effect. It was hypothesized that more pre-injury driving years would moderate the effect of cognition to increase the odds of driving post injury.

RESULTS

Data were missing for 8 variables (out of 13 variables total) and 81 participants (13.9% of participants), for which multiple data imputation was completed. No individual participant was missing data on more than three study variables. Compared to those with incomplete data (n =81), participants with complete data (n = 504) had significantly lower verbal memory scores (*t* (576) = -3.83, *p* < .001), lower executive function scores (*t* (557) = -2.09, *p* < .05), and shorter time since injury (*t* (583) = -2.20, *p* < .05). Additionally, a significantly higher proportion of participants with missing data were not driving at interview ($\chi^2(1) = 4.72$, *p* < .05), experienced a seizure in the past year ($\chi^2(1) = 4.25$, *p* < .05), and had lower family income ($\chi^2(3) = 13.25$, *p* < .01).

The final sample consisted of 585 adults with moderate-to-severe TBI who were enrolled in the TBIMS across the United States and completed a TBIMS follow-up interview. Participants were aged 19-96 years at follow up, and the majority of the sample were males with less than a college education (**Table 1**).

At follow-up interview, 70% (n = 407) of survivors of moderate-to-severe TBI were actively driving a vehicle and 30% (n = 178) were not driving (**Table 1**). Non-drivers were significantly more likely to be Black/African American, have less education, and less family income compared to active drivers. A higher proportion of non-drivers lived in suburban or urban areas, while a higher proportion of drivers lived in rural areas. Non-drivers had more severe head injuries (i.e., significantly longer TFC), were more recently injured, less independent in their motor function, and more likely to have experienced a seizure in the past year.

Table 1. Sample Characteristics (N=585).

	***Active Drivers* (*N* = 407)** *n* (%) or M (SE)	***Non-Drivers* (*N* = 178)** *n* (%) or M (SE)	***Differences by Driving Status***
Age, *years*	46.30 (0.76)	44.87 (1.21)	*t* = 1.03
Range	19 - 93	19 - 96	
Sex, *male*	288 (70.8%)	126 (70.8%)	*b* = 0.001
Race			*b* = **-1.13*****
White	325 (79.9%)	100 (56.2%)	
Black/African American	82 (20.1%)	78 (43.8%)	
Education			*b* = **1.29*****
Less than BA	294 (72.2%)	161 (90.4%)	
BA or higher	113 (27.8%)	17 (9.6%)	
Time Since Injury, *years*	8.59 (0.31)	7.42 (0.51)	*t* = **2.01***
GCS Category			
Mild	110 (27.0%)	49 (27.5%)	
Moderate	46 (11.3%)	19 (10.7%)	
Severe	162 (39.8%)	66 (37.1%)	
Sedated/Unknown	89 (21.8%)	44 (24.8%)	
Time to Follow Commands, *days*	6.78 (0.53)	10.77 (1.25)	*t* = **2.93****
Seizure in the Past Year, *yes*	17 (4.2%)	35 (19.7%)	*b* = **-1.71*****
Motor Function (FIM Motor)	88.56 (0.24)	81.37 (1.09)	*t* = **6.42*****
Family Income			
Less than 25k (reference)	121.8 (29.9%)	114.1 (64.1%)	—
25-49.9k	88.8 (21.8%)	34.1 (19.2%)	*b* = **0.89*****
50-99.9k	101 (24.8%)	21.2 (11.9%)	*b* = **1.50*****
100k or more	95.4 (23.4%)	8.6 (4.8%)	*b* = **2.35*****
Urban-Rural Classification			*b* = **-0.37****
Rural	173.7 (42.7%)	51.8 (29.1%)	
Suburban	143.2 (35.2%)	70.3 (39.5%)	
Urban	90.1 (22.1%)	55.9 (31.4%)	

Pre-Injury Driving, *years* *N* = 568	22.29 (0.79)	21.10 (1.20)	*t* = 0.82
Cognition (BTACT), *z-score*			
Episodic Verbal Memory	-0.67 (0.06)	-1.21 (0.08)	*t* = **5.32*****
Executive Function	-0.58 (0.06)	-1.26 (0.10)	*t* = **6.06*****
Overall Cognition Composite	-0.75 (0.06)	-1.48 (0.10)	*t* = **6.64*****

Note: *p < .05; **p < .01; ***p < .001
BA = bachelor's degree; GCS = Glasgow Coma Scale; FIM = Functional Independence Measure; BTACT = Brief Test of Adult Cognition by Telephone. Data represent an average across 10 iterations of multiple imputation; therefore, frequencies may not add up to 100% due to rounding. For GCS classification, individuals who were intubated (n=123) were assigned a verbal score of 1 for total score calculations. For demographic differences, |t-statistic| (with two-sided *p* value) for continuous variables and unstandardized b-coefficient for categorical variables are provided.

Survivors who were not driving also performed significantly worse across measures of cognitive function compared to drivers, with non-drivers' scores falling more than half a standard deviation below those of drivers (**Table 1**). Better performance on measures of verbal memory and executive function significantly increased the likelihood of driving (**Figure 1 – Unadjusted Model**). Specifically, the odds of driving increased by 36% for every 1 standard deviation increase in verbal memory (OR = 1.36, p < .01) and increased by 38% for every 1 standard deviation increase in executive function performance (OR = 1.38, p < .001).

However, the effects of memory (OR = 1.24, p = .09) and executive function (OR = 1.10, p = .38) on driving were no longer significant when covariates were added to the model (**Figure 1 – Adjusted Model**). History of seizure in the past year significantly decreased the likelihood of driving post-TBI (OR = 0.28, p < .001), such that the odds of driving was 73% lower for survivors who experienced a seizure in the past year compared to those who did not. Greater independence in motor function increased the likelihood of driving post-TBI (OR = 1.08, p < .001), such that the odds of driving increased by 8% for every 1-point increase in FIM Motor score. Lastly, greater family income increased the likelihood of driving post-TBI, such that higher incomes were associated with a higher likelihood of driving relative to the lowest income category of less than $25,000. Specifically, the odds of driving was 210% higher for survivors with $50-99.9k compared to survivors with < $25k (OR = 3.08, $p < .01$), and 480% higher for survivors with ≥ $100k (OR = 5.77, $p < .001$) (see **Supplemental Table** for additional logistic regression statistics). The results did not change when anxiety (GAD-7 total score; OR = 1.01, $p = .97$) was included in the model.

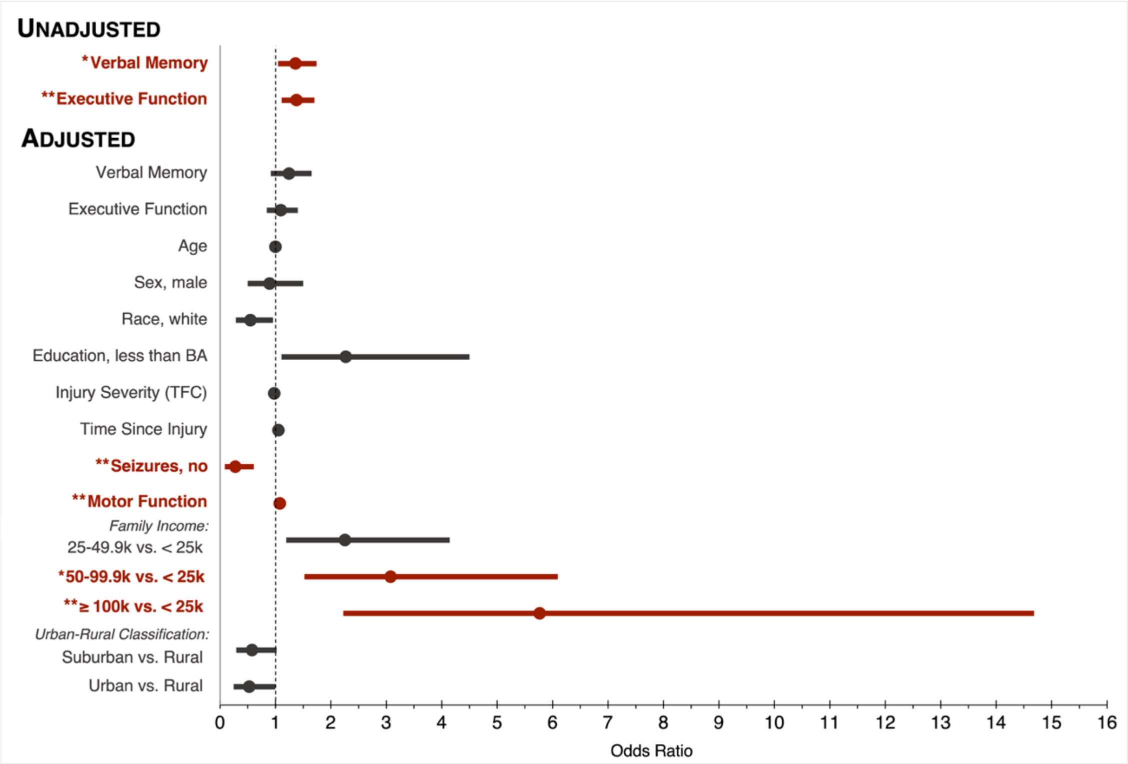

Figure 1. Relationship Between Cognition and Driving Status Post TBI.

Forest plot shows effects unadjusted and effects adjusted for sociodemographic and medical factors. * $p < .05$, ** $p < .005$; Holm-corrected. Odds ratio confidence intervals were not adjusted for multiple comparisons. BA = bachelor's degree; TFC = time to follow commands.

Given that memory and executive function lost significance after the covariates were added to the model, follow-up univariate analyses were conducted to examine if the significant covariates were related to cognitive function. This was done to explore the possibility of a mediation effect, whereby the covariates accounted for the relationship between cognition and driving status. Motor function and family income were significantly associated with verbal memory and executive function, while history of seizures in the past year was not associated to cognition (**Table 2**).

In moderation analyses, the effects of verbal memory and executive function on driving status did not change across the course of recovery (memory–time interaction: OR = 1.03, $p = .34$; executive function–time interaction: OR = 1.00, $p = .91$). Out of the full sample, 568 participants drove prior to their TBI and had complete data to examine if pre-injury driving experience moderated the relationship between cognition and driving status post-injury. The effect of overall cognition on driving status did not change based on a survivor's pre-injury driving experience (interaction between cognition and pre-injury driving experience: OR = 1.00, $p = .39$).

Table 2. Follow-Up Univariate Analyses Examining the Covariates Associated with Cognitive Function.

Cognition on Motor Function [a]

	b-coefficient	SE	*t*	*p*
Verbal Memory	.02	.01	4.89	**< .005**
Executive Function	.04	.01	7.61	**< .005**

Cognition Among Individuals With and Without Seizures in the Past Year [b]

	n	M	SE	*t*	*p*
Verbal Memory					
Seizures, *yes*	52.2	-0.98	0.16	0.96	0.337
Seizures, *no*	532.8	-0.82	0.05		
Executive Function					
Seizures, *yes*	52.2	-0.97	0.20	1.01	0.313
Seizures, *no*	532.8	-0.77	0.06		

Cognition Across Family Income Levels [c]

	n	M	SE	F [d]	*p* [d]
Verbal Memory					
< 25k	235.9	-1.15	0.06	14.04 – 17.36	**all < .005**
25-49.9k	122.9	-0.91	0.10		
50-99.9k	122.2	-0.46	0.12		
100k+	104	-0.48	0.11		
Executive Function					
< 25k	235.9	-1.14	0.09	13.46 – 16.74	**all < .005**
25-49.9k	122.9	-0.85	0.11		
50-99.9k	122.2	-0.49	0.10		
100k+	104	-0.27	0.12		

Note: Holm-corrected *p* values. Predictor variable = covariate, Outcome variable = cognitive domain. [a] The relationships between motor function (via FIM Motor score) and each cognitive domain (verbal memory and executive function) were tested with linear regression analyses. [b] The relationships between seizure history and each cognitive domain were tested with independent-samples t tests. [c] The relationships between family income and each cognitive domain were tested with one-way analysis of variance analyses. [d] Range of F statistics and p values computed for each of the 10 imputations.

DISCUSSION

This study examined cognitive function (memory and executive function) relative to driving status following moderate-to-severe TBI, while also exploring the unique contributions of sociodemographic and medical factors. At cross-sectional follow up, approximately 70% of survivors of moderate-to-severe TBI were actively driving. Greater verbal memory and executive function increased the odds of driving after moderate-to-severe TBI, such that a survivor's odds of driving increased by roughly 40% for every 1 standard deviation increase in their verbal memory and executive function scores. Interestingly, the significant association between cognition and driving washed out when family income and motor function were taken into account. Survivors with higher income were more likely to be driving, and higher income was also associated with better memory and executive function. Similarly, survivors with greater independence in motor function were more likely to be driving, and greater motor function was also associated with better memory and executive function. These findings offer preliminary support for a mediation effect, whereby income and motor function affect cognition, which in turn impacts driving status. While further research is needed to formally test for mediation, the findings provide evidence that verbal memory, executive function, income, and motor function influence one another and are important to consider for driving post-TBI.

These findings highlight the multifaceted nature of return to driving following moderate-to-severe TBI and suggest a more complex, pathway view of cognition. While cognitive function is an important part of the landscape, it is not the sole predictor of driving and other influential factors must also be considered to understand who drives and who does not drive following injury. Thus, the impact of cognition on driving status should be considered within the context of other intervening factors, particularly family income and independence in motor function.

Lower family income is a major barrier to driving after TBI. Relative to survivors with < \$25k in annual household family income, the odds of driving was 210% higher for those with \$50-99.9k and 480% higher for those with ≥ \$100k. Families with lower income may have limited finances to purchase/repair a vehicle (particularly if the survivor sustained their TBI through a motor vehicle collision and the vehicle was no longer drivable) or for insurance expenses. It is also possible that the impact of income on driving status involves a cascade of psychosocial factors. For example, the survivor may not be able to return to work following their injury so now the family is a single income household, and consequently, the caregiver needs to work more and has less time to assist the survivor with returning to drive. More research is needed to better understand the role of income and the specific financial barriers to driving post-TBI.

Less independence in motor function is also a barrier to driving after TBI, over and above the effect of cognition. The odds of driving increased by 8% with every 1-point increase in the FIM Motor score. Prior research suggests that a survivor's decision to return to driving is based on their physical function to a greater extent than their cognitive function, whereby individuals are likely to drive if they have the physical ability to do so regardless of their cognitive ability to safely operate a vehicle.[11] The present findings further support that driving status is more heavily impacted by physical/motor function than cognitive function. This is also reinforced by the fact that 26% of active drivers fell in the impaired range on cognitive testing (based on z scores of -1.5 or below on the BTACT Composite). As suggested by Leon-Carrion et al.,[11] it is possible that patients and families are more focused on the 'visible' physical obstacles to driving and less aware of the 'invisible' cognitive obstacles to safe driving. Given that caregivers often play a central role in deciding if their loved one should return to driving,[3,10] increased education to both patients and caregivers about the cognitive risks for driving is crucial to promote greater awareness and more-informed decision-making about readiness to return to driving after TBI. Along those lines, increased access to professional consultation, including a formal neuropsychological evaluation and on-road driving evaluation, is also important to help identify cognitive risks to driving in order to guide families in making informed decisions about returning to drive. In addition, the current findings also suggest that motor function remains a barrier to driving after TBI, despite advancements in technology and availability of adaptive driving equipment. Survivors may not be connected to local services to receive the adaptive driving equipment they need, or the equipment may be too expensive (another potential financial barrier). Future research should aim to parse out these factors to better understand the specific mechanisms of why motor function is a barrier to driving.

Study Strengths and Limitations

The present study has notable strengths that allow for greater generalizability of results. First, the study included a large, geographically diverse sample of participants who sustained a moderate-to-severe TBI. Second, this was the first known study to utilize validated, telephone-administered cognitive testing to examine the impact of cognition on return to driving following TBI. The literature on cognitive function post TBI is predominantly limited to studies that required participants to complete cognitive testing in person, which raises concerns about sample and attrition biases. Telehealth services may promote greater access and utilization of cognitive testing in underserved populations.[39] Additionally, among survivors of TBI who have not returned to driving, telehealth cognitive testing offers a solution to their primary barrier of transportation to the testing site. By eliminating in-person testing barriers, the findings may be more representative of the overall TBI population compared to prior studies of cognition and return to driving. Third, this was the first known study to examine the influence of family income on driving status using defined income brackets. Fourth, the present study examined driving status across an extended duration of recovery (up to 30 years post injury) compared to most other studies that were limited to 5 years.

On the other hand, the cross-sectional design of this study limits interpretation of driving status across recovery. Driving status may not be static, thus longitudinal assessments are needed in the future to address questions of how the association of cognition on driving status changes across the recovery trajectory. Likewise, financial status (and employment status) may change over time and should be considered in longitudinal studies on return to driving. Access to other modes of transportation may explain why some survivors did not return to driving after injury, but unfortunately, the present study did not have data to directly examine this. Future studies should address whether having access to other modes of transportation (e.g., public transit) influences driving status after TBI.

The multiple imputation also limited the study's ability to formally test for a mediation effect, thus future research is needed to determine the exact sequence by which cognition, income, and motor function impact one another and driving status. Furthermore, the sample is limited to individuals who self-identified as white or Black and predominantly comprised of individuals of non-Hispanic ethnicity (96% of sample). Individuals who self-identified as a race other than white or Black were excluded due to small sample sizes. Consequently, the results may not generalize to individuals of other races and ethnic backgrounds. Future research with more racially and ethnically diverse samples is imperative for understanding return to driving in the overall TBI population. Lastly, the current study did not examine fitness to drive. Whether or not a survivor is driving is just as important as their fitness to drive. Therefore, it will be useful for future studies to examine memory, executive function, income, and motor function within the context of driving performance to better understand how these factors impact driving after TBI.

Conclusion

Verbal memory, executive function, family income, and independence in motor function are all important to consider for driving after moderate-to-severe TBI. Survivors with family income < $25k and those with motor limitations are particularly at risk for not being able to return to driving. Clinically, it is important to keep these factors in mind when seeing patients. Tailored education about cognitive barriers to driving should be provided to survivors and caregivers. It is also essential to consider the impact of financial and motor limitations on a patient's recovery in order to promote community reintegration and return to productive roles. Given the enormous toll driving cessation has on community reintegration after TBI, future research should aim to parse out the specific mechanisms of why income and motor function are barriers to driving in order to inform future policies and development of recovery services that offset barriers to driving.

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Supplemental Table: Logistic Regression.

Unadjusted Model	*OR*
Verbal Memory	**1.36 ***
Executive Function	**1.38 ****
Adjusted Model	*OR*
Verbal Memory	1.24
Executive Function	1.10
Age	1.00
Sex	0.90
Race	0.55
Education	2.27
Injury Severity (TFC)	0.98
Time Since Injury	1.05
Seizures	**0.28 ****
Motor Function	**1.08 ****
Family Income [1]: 25-49.9k vs. < 25k	2.25
Family Income [2]: 50-99.9k vs. < 25k	**3.08 ***
Family Income [3]: ≥ 100k vs. < 25k	**5.77 ****
Urban-Rural Classification [1]: Suburban vs. Rural	0.58
Urban-Rural Classification [2]: Urban vs. Rural	0.53

Note: *** *p* < .05 ** *p* < .005**; Holm-corrected.
OR = odds ratio; CI = confidence interval; TFC = time to follow commands.

THE ROLE OF COGNITION AND SELF-AWARENESS ON DRIVING PATTERNS AFTER MODERATE-TO-SEVERE TRAUMATIC BRAIN INJURY

by

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Format adapted for dissertation

ABSTRACT

Objective: To examine the influence of cognition and self-awareness on driving patterns (frequency and restriction) following moderate-to-severe traumatic brain injury (TBI). **Participants and Methods:** Participants were 350 adults aged 19-87 years (mean age = 46 years; 70% male) with history of moderate-to-severe TBI who resumed driving and were enrolled in the TBI Model System. Cross-sectional data were obtained ranging 1-30 years post injury, including questions on driving practices, the Brief Test of Adult Cognition by Telephone (BTACT), and the Functional Independence Measure (FIM). Self-awareness of cognitive function was measured via the discrepancy between objective cognitive testing (BTACT) and self-reported cognitive function (FIM Cognition subscale). Regression analyses were conducted to examine the relationships between cognition, self-awareness, and each driving outcome, followed by causal mediation analyses to examine the mediating effect of self-awareness. **Results:** Thirty-nine percent of survivors had impaired self-awareness, 88% of survivors drove numerous times per week, and the average survivor reported limited driving in 6 situations. Worse cognitive function was significantly related to impaired self-awareness and more restricted driving behavior. Cognition was not related to driving frequency, and self-awareness did not mediate the relationships between cognition and driving practices. **Conclusion:** Most survivors who drive after their injury are driving frequently, but the situations they drive in differ based on their cognitive ability. Future research needs to focus on how cognition affects nuanced aspects of driving behavior post injury (i.e., situations survivors drive in).

Keywords: *brain injuries; neurocognition; self-awareness; driving*

INTRODUCTION

Driving a vehicle is a fundamental activity of daily living for most adults in the United States. Being able to drive after moderate-to-severe traumatic brain injury (TBI) is a key step to gaining independence, community reintegration, and quality of life.[1-5] Driving is also often tied to one's identity and sense of self as an adult.[3] Understandably, return to driving after moderate-to-severe TBI is a primary goal for many survivors and caregivers.

Driving a vehicle is a complex activity that requires a range of cognitive abilities, including executive function.[6] Lasting cognitive deficits are common after moderate-to-severe TBI and potentially hinder driving performance.[6-8] Nevertheless, a large proportion (roughly 70%) of survivors of moderate-to-severe TBI return to driving after their injury.[9] Given the substantial benefits driving has on day-to-day life and well-being, survivors are often eager to resume driving and may do so despite having residual cognitive limitations from their injury that put them at risk on the road.[5,10,11] Thus, rather than ceasing to drive, research suggests survivors may return to driving but then modify or limit their driving as a self-regulatory strategy to compensate for impairments from their injury.[5,12-14] For example, relative to before their injury, survivors who returned to driving after their injury drove less frequently, shorter distances, and avoided driving at night and in busy traffic.[13] However, in order to successfully modify one's driving behavior to ensure safety, one must be aware of having had a brain injury and of residual cognitive impairments that could negatively impact driving performance. Therefore, it is necessary to consider the role of both cognition and self-awareness in driving after moderate-to-severe TBI.

Impaired self-awareness from brain injury reflects disturbances in subjective experience and reduced insight into one's own condition, whereby the survivor is not aware of significant changes in functional abilities.[15-17] Disturbances in self-awareness are common following moderate-to-severe TBI, as 30-50% of survivors exhibit self-awareness impairments 6+ months post injury with impairments shown up to 5 years post injury.[18-21] Additionally, self-awareness difficulties often vary by domain, such that unawareness of cognitive deficits is more common and lasting than unawareness of physical or sensory disturbances.[16,21-23] Unfortunately, survivors of TBI with poor self-awareness often have worse outcomes.[16,18,24,25] From a neurorehabilitation standpoint, self-awareness is necessary to utilize strategies to compensate for deficits and minimize detrimental effects of impairments on daily functioning.[18,20,24,26,27] Thus, if survivors are not aware of their cognitive shortcomings, then they are unable to adjust their behavior and implement strategies to compensate for cognitive deficits.

The literature supports that self-awareness of deficits influences driving ability.[3,26,28,29] Among individuals with acquired brain injury, better self-awareness of deficits was strongly related to better on-road driving performance.[30] Additionally, self-awareness moderated the relationship between cognition and driving performance, whereby cognitive impairments were more detrimental to driving performance among individuals with impaired self-awareness.[30] Given the cognitive demands that come with driving, poor awareness of cognitive deficits poses risks for driving safety. Prior studies offer preliminary support that self-awareness is important for self-monitoring and utilizing compensatory strategies to make up for cognitive impairments and aid driving performance.[26,30,31]

However, the current literature examining cognition and self-awareness in driving is limited. First, research examining the impact of cognition on driving is heavily focused on fitness to drive. Given the large proportion of survivors who return to driving, research is needed to examine how cognitive function impacts survivors' driving patterns after injury. Second, studies looking at self-awareness in driving after TBI are sparse, limited by small samples, and have primarily examined on-road driving test performance, rather than driving practices in daily life. It is important to examine how self-awareness impacts driving patterns in daily life, particularly since survivors may return to driving without formal driving evaluation[5,32] or despite professional recommendations not to drive.[10,11] In the only known study looking at driving patterns, survivors with intact self-awareness drove more miles than survivors with impaired self-awareness.[6] However, other aspects of driving are also important to explore, such as how frequently survivors drive and situations they drive in. Third, prior studies examining the relationship between self-awareness and driving mostly looked at broad self-awareness function. Research suggests that self-awareness is multidimensional, varies by activity, and tends to be more impacted in higher-order, complex domains of function after TBI (e.g., cognition), thus an activity-specific approach to measuring self-awareness is optimal.[21,27] Given that cognition is a higher-order domain that plays a key role in driving, self-awareness of cognitive function is a key dimension of awareness to focus on.

To address these gaps, the current study aimed to examine the influence of cognition and self-awareness on current driving patterns (frequency and restrictions) in a large, multicenter sample of survivors of moderate-to-severe TBI who returned to driving. Among the types of self-awareness thoroughly described in the literature,[17,33-35] the current study focused on examining metacognitive aspects of self-awareness, which involve an individual's knowledge and perception of their functioning and capabilities. First, it was hypothesized that better cognitive function would be directly related to more frequent and less restricted driving after TBI. Second, it was hypothesized that self-awareness would partially mediate the relationships between (1) cognition and driving frequency and (2) cognition and restricted driving behavior following moderate-to-severe TBI. Specifically, it was expected that individuals with intact awareness of their cognitive function would employ more compensatory strategies (i.e., drive less frequently and place more restrictions on their driving) to make up for cognitive limitations, while those with impaired awareness would not.

METHODS

Participants and Procedures

The current sample was comprised of individuals enrolled in the Traumatic Brain Injury Model System (TBIMS) across eight centers in the United States. All participants had a history of moderate-to-severe TBI, presented to the emergency department within 24 hours of their injury, and subsequently received inpatient acute care and rehabilitation at a TBIMS-affiliated center. At time of enrollment, participants were at least 16 years old and provided informed consent personally or through a legally authorized representative.

TBIMS follow-up interviews occur 1, 2, and 5 years after injury and every 5 years thereafter. All TBIMS participants who were eligible for a follow-up interview from May 1, 2018 to May 31, 2019 were contacted by telephone to complete the standard interview and provided the option to complete a driving survey. The standard TBIMS interview included questions on demographics, injury characteristics, and cognitive function. The driving survey took an additional 15-20 minutes, was completed by phone or mail, and included questions on driving frequency and practices after injury. Cross-sectional driving data were obtained for participants across the recovery trajectory, extending from 1-30 years post injury. Additional details on the TBIMS driving survey data collection procedures have been provided by Novack et al.[9]

The present study involved secondary, cross-sectional analysis of participants enrolled in the TBIMS who completed the driving survey and returned to driving after injury. Additional exclusion criteria for the current analyses included not driving at the time of interview (n = 178), self-identified race other than white or Black (n = 13), incomplete data on one or more study variables (n = 52), and disruptions in self-awareness due to hypervigilance of deficits / exaggeration of impairment (n = 5). Participants who exhibited exaggeration of impairment (poor self-reported cognition with intact cognitive test performance) were excluded to avoid potential confusion when interpreting results since the literature did not provide clear guidance on how to handle impaired awareness due to hypervigilance among survivors of TBI. The majority of participants self-identified as white (77.4%) or Black (19.5%), thus those who self-identified as a race other than white or Black (3.2%) were excluded due to sample sizes too small for meaningful analysis.

Measures

Predictor – Cognitive Function

The *Brief Test of Adult Cognition by Telephone* (BTACT),[36] a brief telephone-administered cognitive test battery, was administered to all participants during the standard TBIMS interview. Prior studies showed that the BTACT is a valid and feasible measure of cognition among survivors of moderate-to-severe TBI.[37-39] The battery consists of six subtests that are combined to create the *BTACT Composite,* a measure of overall cognitive function. The individual subtests that make up the overall composite assess the following cognitive skills: verbal learning and recall adapted from the Rey Auditory Verbal Learning Test,[40] working memory via the Wechsler Adult Intelligence Scale-III Digit Span backward,[41] processing speed via timed backwards counting,[42] category verbal fluency,[43] and reasoning via number sequencing pattern completion.[36]

Outcomes – Driving Frequency and Restricted Driving Behavior

As part of the TBIMS driving survey,[9] participants who were driving at the time of interview were asked, "*In the past month, how often have you been driving a car, truck, or motorcycle?*", with six response options ranging from "daily" to "less than once a month." Due to few endorsements on several of the response options, categories were collapsed into two levels: 'driving more than once a week' versus 'once a week or less.' Further details on the driving survey are provided by Novack et al.[9]

Drivers were also asked to rate how much they drive in 15 situations (**Table 1**), ranging from "not at all" to "very much" on a 5-point Likert scale. The lowest two ratings (i.e., "not at all" and "a little bit") were combined to reflect restricted driving in the situation. To examine the use of compensatory strategies,[30] a total driving restriction score was derived for each participant as the sum of the situations described as restricted.[44] The driving restriction score ranged from 0-15, reflecting the total number of driving situations the survivor described as restricted (i.e., higher total scores indicated restrictions in more driving situations, with 0 reflecting no restrictions in any situations and 15 reflecting restrictions in all driving situations).

Table 1. Driving Situations.

“Rate how much you drive in the following situations” **Drive…**	
alone (no one else in vehicle or on the motorcycle)	when turning left across oncoming traffic
in your local area	at high speeds (at or above 60 mph)
in heavy traffic (like rush hour)	on the highway (such as an interstate)
in unfamiliar areas	in a city
at night	long distances (> 30 miles at one time)
with people in the vehicle or on the motorcycle	when the weather is bad
when you might have to pass another vehicle on a two-lane road	when you must consult a map or use a GPS device
when merging in traffic is required	

Mediator – Self-Awareness

To examine awareness of cognitive function, participants’ subjective self-report of cognitive function in daily activities was compared to their objective cognitive test performance. Objective cognitive impairment (via cognitive testing) was defined as a BTACT Composite z-score of ≤ -1.0.[45] For measuring subjective cognition, as part of the standard TBIMS follow-up interview, participants completed the *Functional Independence Measure* (FIM),[46,47] which assessed disability in carrying out activities of daily living. The instrument is subdivided into motor and cognitive subscales.[48] The *FIM Cognitive* subscale (FIMCog),[48] a measure of cognitive disability, was comprised of 5 items that assess ability to complete daily activities requiring cognitive skills: comprehension (of complex or abstract information), expression (of complex or abstract ideas clearly and fluently), social interaction (skills related to getting along and participating with others), problem-solving (solving complex problems of daily living), and memory (skills related to recognizing and remembering while performing daily activities). Participants rated how much assistance they needed to complete each activity from 1-7, with higher ratings indicating greater independence and a 5 or lower indicating need for caregiver assistance (**Table 2**). Item scores were summed to create the FIMCog total score, ranging from 5-35.

In the present study, subjective cognitive impairment (via self-reported cognition) was defined as a FIMCog score of ≤ 28.[49,50] This cut-off was informed by prior studies that found a FIMCog cut-off score of 29 predicted discharge destination (private residence versus residential care facility) after inpatient rehabilitation among patients with clinical suspicion of cognitive impairment,[49] FIMCog scores ≥ 28 predicted successful discharge home to live alone among patients receiving inpatient rehabilitation following stroke,[50] average Mini-Mental State Examination scores of 23.4 (i.e., close to the cognitive impairment cut-off score of 24) strongly correlated with average FIMCog scores of 28.2,[51] and studies that defined impaired daily living function as a rating of ≤ 5 on one or more of the FIMCog items.[52,53]

Table 2. Description of FIM Item Ratings.

Item Score	Classification
7	Complete Independence (Timely, safely)
6	Modified Independence (Extra time, device)
5	Supervision (performs 100%, but needs supervision)
4	Minimal Assist (≥ 75%)
3	Moderate Assist (50 - 74%)
2	Maximal Assist (25 - 49%)
1	Total Assist (< 25%)

Covariates

Sociodemographic factors. Age at interview, sex assigned at birth (male, female), self-identified race (white, Black), education (less than bachelor's degree (BA), BA or higher), urban-rural classification (rural, suburban, urban), and family income (in thousands, < 25, 25-49.9, 50-99.9, 100+) were collected by self-report during the standard TBIMS interview.

Medical factors. TBI severity was measured via time to follow commands (TFC, in days), which was obtained during hospitalization following injury as part of the standard TBIMS data collection protocol. Time since injury (years), history of seizures in the year prior to interview (yes/no), and motor function (via the FIM Motor total score) were collected during the interview. The FIM Motor[47,48] subscale was comprised of 13 items assessing how much assistance a person needs to complete daily activities that require physical function: eating, grooming, bathing, dressing the upper body, dressing the lower body, toileting, bladder management, bowel management, transfers to bed/chair/wheelchair, transfers to toilet, transfers to tub/shower, locomotion (walking or wheelchair propulsion), and stair climbing. Participants rated how much assistance they needed to do each activity from 1-7, with 1 indicating total assistance and 7 indicating complete independence. The FIM Motor total score ranged from 13 to 91, with higher scores representing greater independence in physical function.

Sensitivity Analysis

Given that anxiety may affect post-injury driving patterns, sensitivity analyses were conducted using the General Anxiety Disorder Scale–7 (GAD-7),[54] a validated screening measure for generalized anxiety disorder. The GAD-7 was administered as part of the standard TBIMS follow-up interview. Participants rated how often they experienced seven defining symptoms of GAD over the last two weeks from 0-3, with 0 indicating “not at all” and 3 indicating “nearly every day.” The GAD-7 total score for the seven items ranged from 0 to 21, with higher scores indicating more anxiety symptoms.

Data Reduction

BTACT Composite

For the cognitive data, 12 participants were unable to complete the entire BTACT cognitive battery due to cognitive reasons (i.e., their BTACT Composite score was derived from data with scores assigned on at least one subtest: n=7 were missing one subtest and n=5 missing all six subtests). Thus, following recommended BTACT scoring methods,[55] subtest raw scores of 0 were assigned for those individuals (as such, these scores were not counted as missing data). The BTACT raw data were standardized to *z* scores by age decade, sex, and education.[55] For one participant aged 19 years, community comparison sample data[55] from the 20-30s age decade were used.

Self-Awareness Score

A self-awareness score was derived by calculating the discrepancy rating between objective (BTACT Composite test performance) and subjective (FIMCog self-report) measures. Discrepancy between test performance and self-report indicated inaccurate perception of cognitive abilities (i.e., impaired awareness). The dichotomized subjective self-report rating (0 = intact, 1 = impaired) was subtracted from the dichotomized objective rating (0 = intact, 1 = impaired). Thus, a discrepancy score of 0 indicated accurate estimation (intact self-awareness), +1 indicated overestimation of cognitive ability (impaired self-awareness), and -1 indicated underestimation of performance (exaggeration of impairment or hypervigilance of deficits, i.e., impaired subjective rating with intact objective rating). Similar dichotomization methods and calculation of discrepancy scores have been previously published.[19,33,56-58] After excluding participants who exhibited exaggeration of impairment, the final self-awareness score had two levels: intact awareness (agreement between self-report and test performance) versus impaired awareness (discrepancy due to overestimation of cognitive ability).

Data Analysis

Statistical analyses were performed in the R software environment[59] version 4.1.3. Differences between participants with complete and incomplete data were examined with independent samples t test (for BTACT Composite, driving restriction, age, TFC, time since injury, and motor function) and Pearson chi-square test (for driving frequency, sex, race, education, seizure history, income, and urban-rural classification). Demographic differences in driving restriction (continuous) were tested with linear regression (for age, TFC, time since injury, and motor function), independent-samples *t* test (for sex, race, education, and seizure history), and one-way ANOVA (for income and urban-rural classification). Differences in driving frequency (dichotomous) were tested with binary logistic regression.

Causal Mediation Analysis

Statistical models to examine mediation were constructed based on methods described by Baron and Kenny.[60] For each of the driving outcomes (frequency and restriction), regression Models 1, 2, and 3 were constructed. Model 1 examined the total effect of cognitive function on the driving outcome of interest (path *c*). Model 2 tested the effect of cognitive function on self-awareness (path *a*). Model 3 examined the effect of self-awareness on the driving outcome, while accounting for cognitive function (path *b* and path *c'*). For the driving frequency outcome, binary logistic regression was used for all three models. For the driving restriction outcome, multiple linear regression was used for Models 1 and 3 and binary logistic regression for Model 2. The covariates (listed above) were accounted for in all models. Holm multiple test corrections were applied to *p* values to protect against inflation of Type I error.[61] The assumptions for linear regression and binary logistic regression were tested and met.

For each of the driving outcomes, causal mediation analysis was conducted using the "*mediation*" R package[62] in order to formally test the mediation effect. Models 1 and 3 were included in the causal mediation analysis, and quasi-Bayesian approximation[63] with 1,000 Monte Carlo simulation samples[64] were used to generate causal mediation estimates and 95% confidence intervals for the indirect effect [average causal mediation effect (ACME)] and the average direct effect (ADE).

Sensitivity Analyses

As there is no known established consensus at this time for a FIMCog cut-off score of impairment, the self-awareness score was derived using different cut-off scores based on a minimal clinically important difference of 3 points on the FIMCog.[65] Thus, sensitivity analyses were conducted with FIMCog scores ≤ 25 and ≤ 31 to reflect subjective cognitive impairment. Awareness scores were re-generated using the lower and upper FIMCog cut-off scores, then regression and mediation analyses were re-run. Additionally, analyses were also repeated with anxiety (GAD-7) included as a covariate in the models.

RESULTS

The final sample was 350 adults with history of moderate-to-severe TBI who returned to driving a vehicle. The sample was primarily comprised of individuals who identified as non-Hispanic white males and had less than a college education (**Table 3**). On average, individuals performed within the low average range on cognitive testing (**Table 3**), although there was a wide distribution of *z* scores ranging from -5.86 to 2.93. Regarding subjective cognitive function, the average individual denied needing assistance to complete cognitive activities (**Table 3**) (FIMCog score range: 19–35). Out of the 350 drivers, 61% (n = 214) had intact self-awareness and 39% (n = 136) had impaired self-awareness of their cognitive function.

Cognitive function was significantly related to self-awareness, whereby for every 1 standard deviation *increase* in cognition (*z* score), the odds of impaired self-awareness *decreased* by 97% (**Tables 4 and 5**). Cognition and the study covariates explained 67% of the variability in self-awareness ($R^2 = 0.673$). Surprisingly, individuals with more independence in motor function were significantly more likely to have impaired self-awareness, such that the odds of impaired self-awareness *increased* by 28% for every 1 point *increase* on the FIM Motor subscale (**Tables 4 and 5**).

Table 3. Sample Characteristics (N=350).

Age, M (SD), *years*	46.03 (14.85)
Range	19 - 87
Sex, *n* (%), *male*	245 (70.0%)
Race, *n* (%)	
White	275 (78.6%)
Black/African American	75 (21.4%)
Ethnicity, *n* (%), non-Hispanic	337 (96.3%)
N = 346	
Education, *n* (%)	
Less than BA	252 (72.0%)
BA or higher	98 (28.0%)
Time Since Injury, M (SD), *years*	8.71 (6.44)
GCS Category, *n* (%)	
Complicated Mild	89 (25.4%)
Moderate	34 (9.7%)
Severe	73 (20.9%)
Intubated	75 (21.4%)
Sedated/Unknown	79 (22.6%)
Time to Follow Commands, M (SD), *days*	6.63 (10.39)
Seizure in the Past Year, *n* (%), *yes*	13 (3.7%)
Motor Function (FIM Motor), M (SD)	88.69 (4.93)
Family Income, *n* (%)	
Less than 25k	99 (28.3%)
25-49.9k	73 (20.9%)
50-99.9k	95 (27.1%)
100k or more	83 (23.7%)
Urban-Rural Classification, *n* (%)	
Rural	148 (42.3%)
Suburban	124 (35.4%)
Urban	78 (22.3%)
Cognitive Function, M (SD)	
BTACT Overall Cognition Composite, *z-score*	-0.71 (1.18)
FIM Cognitive Score (self-report)	32.99 (2.16)
Self-Awareness, *n* (%), *impaired*	136 (38.9%)

Driving Frequency, *n* (%)	
More than once a week	307 (87.7%)
Once a week or less	43 (12.3%)
Driving Restriction Score, M (SD)	6.01 (4.01)

Note: M = mean; SD = standard deviation; BA = bachelor's degree; GCS = Glasgow Coma Scale; FIM = Functional Independence Measure; BTACT = Brief Test of Adult Cognition by Telephone. The Driving Restriction Score reflects the number of driving situations that participants described as restricted (out of 15 total situations).

Regarding driving patterns, 88% of survivors (n = 307) were driving numerous times per week (**Table 3**), with the majority of those individuals driving every day (81%, n = 249) and a smaller proportion driving several times a week (19%, n = 58). Surprisingly, neither cognition nor self-awareness were related to driving frequency (**Table 4**). There was not a significant mediation effect, as self-awareness mediated only roughly 2% of the relationship between cognition and driving frequency after TBI (**Table 6**). Overall, for the driving frequency outcome, the relationship between cognition and self-awareness (path *a*; Model 2) was significant, while the other paths were not (**Figure 1**).

Table 4. Regression Models for Driving Frequency.

PREDICTORS	Driving Frequency on Cognition *OR*	Self-Awareness on Cognition *OR*	Driving Frequency on Self-Awareness *OR*
Self-Awareness, *impaired*	—	—	1.67
Cognition	1.35	**0.03** ***	1.52
Age	1.01	1.01	1.01
Sex, *female*	0.98	1.30	0.98
Race, *Black*	1.67	2.29	1.57
Education, *BA or higher*	1.04	1.67	0.99
TBI Severity (TFC)	0.99	1.00	1.00
Time Since Injury, *years*	1.10	1.03	1.09
Seizure History, *yes*	2.47	0.80	2.49
Income:			
$25-49.9k vs. < 25k	2.97	0.87	2.89
$50-99.9k vs. < 25k	1.48	0.72	1.49
$100k + vs. < 25k	5.07	0.74	5.12
Motor Function (FIM)	1.09	**1.28** **	1.09
Urban-Rural:	1.55	0.54	1.70
suburban vs. rural			
urban vs. rural	0.42	0.72	0.44

Note: ***** $p < 0.001$**; **** $p < 0.01$**; *** $p < 0.05$**; Holm-corrected.
BA = bachelor degree; TFC = time to follow commands; FIM = Functional Independence Measure.
Odds ratios (OR) from binary logistic regression with Holm-corrected *p* values.

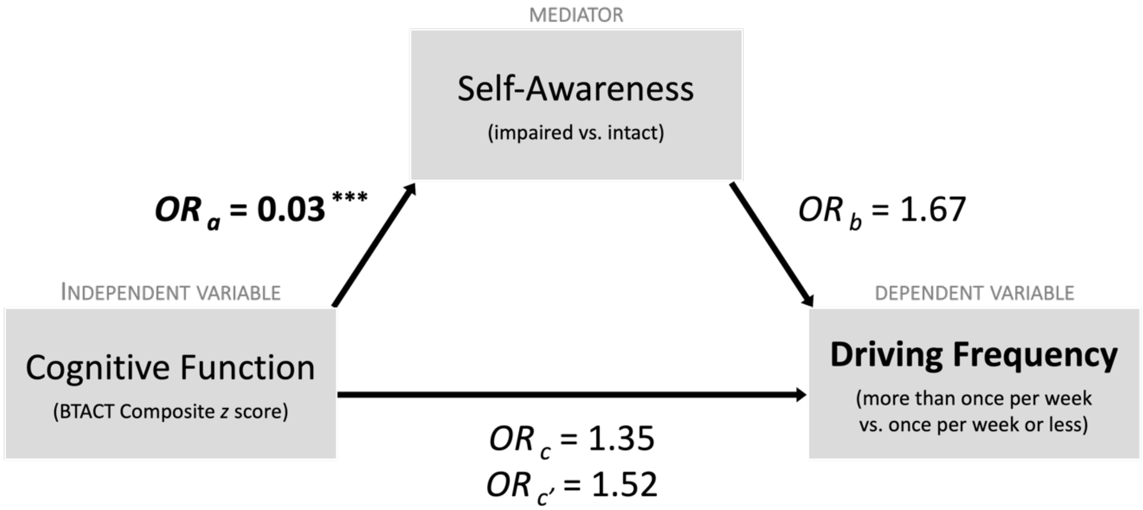

Figure 1. Mediation Model for Driving Frequency.
*** $p < .001$; Holm-corrected. Pathways are odds ratios (OR). OR_a represents the relationship between cognitive function and self-awareness. OR_b represents the relationship between self-awareness and driving frequency, while accounting for cognitive function. OR_c represents the relationship between cognitive function and driving frequency. $OR_{c'}$ represents the relationship between cognitive function and driving frequency with self-awareness as a mediator (i.e., the average direct effect).

On average, survivors restricted their driving in 6 situations (**Table 3**), with half of survivors (50.6%, n = 177) avoiding six or more situations. Cognitive function was significantly related to restricted driving behavior. For every 1 standard deviation *increase* in cognitive performance (*z* score), a survivor reported restricted driving in one *less* situation (i.e., the number of restricted driving situations decreased by 1 out of 15) (**Table 5**). Cognition and the covariates explained 21% of the variability in restricted driving behavior (multiple $R^2 = 0.208$). Age and time since injury were also significantly related to restricted driving. As age increased, individuals reported restricted driving in more situations, and more time since injury was related to less restricted driving (**Table 5**). Self-awareness was not related to restricted driving (**Table 5**), and there was not a significant mediation effect, as self-awareness mediated only 1% of the relationship between cognition and restricted driving behavior after TBI (**Table 6**). Taken together, for the restricted driving outcome, the relationship between cognition and self-awareness (Model 2, path *a*) was significant and the relationship between cognition and restricted driving (Model 1, path *c*; Model 3, path *c'*) was significant, while the other paths were not (**Figure 2**).

Table 5. Regression Models for Driving Restriction.

PREDICTORS	**Driving Restriction on Cognition** b^a	**Self-Awareness on Cognition** OR^b	**Driving Restriction on Self-Awareness** b^a
Self-Awareness, *impaired*	—	—	0.28
Cognition	**-0.79** ***	**0.03** ***	**-0.71** *
Age	**0.06** ***	1.01	**0.06** ***
Sex, *female*	0.85	0.77	0.85
Race, *Black*	-0.13	2.29	-0.17
Education, *BA or higher*	-0.27	1.67	-0.29
TBI Severity (TFC)	0.03	1.00	0.03
Time Since Injury, *years*	**-0.10** *	1.03	**-0.10** *
Seizure History, *yes*	2.01	0.80	2.01
Income:			
\$25-49.9k vs. < 25k	-1.63	0.87	-1.64
\$50-99.9k vs. < 25k	-0.95	0.72	-0.95
\$100k + vs. < 25k	-1.50	0.74	-1.50
Motor Function (FIM)	-0.09	**1.28** **	-0.10
Urban-Rural:			
suburban vs. rural	-1.01	0.54	-0.98
urban vs. rural	-0.68	0.72	-0.65

Note: *** **$p < 0.001$**; ** **$p < 0.01$**; * **$p < 0.05$**; Holm-corrected. BA = bachelor's degree; TFC = time to follow commands; FIM = Functional Independence Measure. [a] Unstandardized coefficients from linear regression with Holm-corrected p value; [b] Odds ratios (OR) from binary logistic regression with Holm-corrected p value.

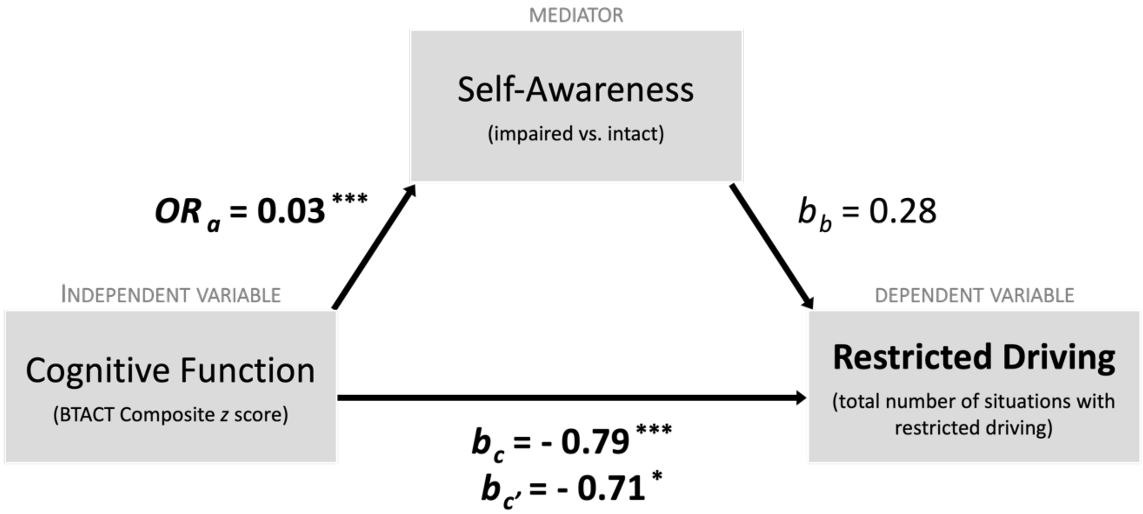

Figure 2. Mediation Model for Restricted Driving Behavior.

*** $p < .001$; * $p < .05$; Holm-corrected. Pathways are unstandardized b-coefficients (b) or odds ratios (OR). OR_a represents the relationship between cognition and self-awareness. b_b represents the relationship between self-awareness and restricted driving behavior, while accounting for cognition. b_c represents the relationship between cognition and restricted driving. $b_{c'}$ represents the relationship between cognition and restricted driving with self-awareness as a mediator (i.e., the average direct effect).

Table 6. Causal Mediation Analysis Estimates.

Model Outcome	ACME	ADE	Total Effect	Prop Mediated
Driving Frequency	-0.000847	0.031641 *	0.030794 *	-0.021101
Driving Restriction	-0.0105	-0.6963 **	-0.7068 **	0.0101

Note: ** $p < 0.01$; * $p < .05$; ACME = average causal mediation effect of self-awareness on the relationship between cognition and driving outcomes; ADE = average direct effect; prop mediated = proportion of total effect mediation (ratio of causal mediation effect to total effect).

Driving outcomes differed based on demographic variables. Older participants were significantly more likely to restrict their driving in more situations (F (348) = 9.6, $p < 0.005$), while age was not significantly related to driving frequency ($p = 0.58$). Individuals further out from injury were significantly more likely to drive frequently (i.e., more than once per week) (OR = 1.08, $p < 0.01$) and to restrict their driving less (F (348) = 5.47, $p < 0.05$). Better motor function was significantly related to less restricted driving (F (348) = 14.28, $p < 0.001$) and more frequent driving (OR = 1.12, $p < 0.001$). Participants with history of seizure in the past year restricted their driving in significantly more situations (mean = 8.3) compared to participants without history of seizure (mean = 5.9) (t (13.50) = -2.61, $p < 0.05$). Meanwhile, driving frequency was *not* related to history of seizure ($p = 0.61$). Higher family income was related to less restricted driving (F (3) = 6.25, $p < 0.001$). Participants with the highest income (≥ $100k) were more likely to drive frequently compared to those with the lowest income (< $25k) (OR = 6.75, $p < 0.005$), but driving frequency did not differ between participants with income of $25-49.9k compared to < $25k ($p = 0.06$) nor between those with income of $50-99.9k compared to < $25k ($p = 0.23$). Driving restriction and driving frequency did *not* differ by sex, race, education, injury severity, nor urban-rural classification (all $p > 0.05$).

Individuals with complete data across all study variables differed from those with incomplete data (who were ultimately excluded; n = 52). Participants with incomplete data scored significantly lower on the BTACT Composite (M = -1.20, SD = 1.09) compared to those with complete data (M = -0.70, SD = 1.17) (t (383) = -2.22, $p = 0.027$). A higher proportion of participants with incomplete data had impaired self-awareness (65%, n = 17) compared to those with complete data (39%, n = 136) (χ^2 (1) = 7.06, $p = 0.008$). A higher proportion of participants with incomplete data were of lower income categories (78% with < \$50k annual income, n = 25) compared to those with complete data (49% with < \$50k, n = 174) ($\chi^2(3) = 11.90$, $p = 0.008$). Individuals with complete versus incomplete data did not differ on driving frequency, driving restriction, age, sex, race, education, urban-rural classification, injury severity, time since injury, motor function, nor seizure history (all $p > 0.05$). Fortunately, no single study variable had more than 10% missing values.

Sensitivity Analyses

A series of sensitivity analyses were conducted to determine whether the effect of self-awareness changed based on varying FIMCog cut-off scores of impairment. With a FIMCog cut-off score of ≤ 25, 42% (n = 146) of the sample had impaired awareness, which was a marginal increase from the rate of impaired awareness in the main analysis (39%). For Model 2 (binary logistic regression testing the relationship between cognition and self-awareness), motor function was no longer significantly related to self-awareness, otherwise the results remained the same. *For driving frequency*, there was no change in the results for Model 3. For the sensitivity causal mediation analysis, the ADE and total effect lost significance (although the changes in the estimates were minimal), otherwise there were no other changes. Of note, the significant findings in the main causal mediation analysis were negligible given that the ADE and total effect were never significant in the individual regression models for driving frequency. Thus, the changes in the sensitivity analysis results were largely consistent with the overall findings. *For driving restriction*, in Model 3 (linear regression testing the relationship between self-awareness and driving restriction, while accounting for cognition), cognition lost significance following Holm correction due to a slight increase in the b-coefficient for self-awareness (although still nonsignificant). Otherwise, there were no other changes, and the results remained the same for the causal mediation analysis.

With a FIMCog cut-off score of $\leq$ 31, n = 32 were newly classified with hypervigilance of deficits and thus excluded, so the total sample size decreased to 318. Among the 318 participants, 36% (n = 115) had impaired awareness, which was a marginal decrease from the rate of impaired awareness in the main analysis. The results remained the same across all analyses (i.e., Model 2, Model 3, and the causal mediation analysis for both driving frequency and driving restriction outcomes).

When anxiety (GAD-7 total score) was included in the models, the findings generally remained the same. Specifically, there were no significant changes in the results for Model 1, Model 3, and the causal mediation analysis when examining driving frequency, and no changes for Model 1 and the causal mediation analysis when examining driving restriction. Regarding Model 3 for driving restriction (relationship between self-awareness and driving restriction, while accounting for cognition), cognition lost significance following Holm correction, but self-awareness remained non-significant. For Model 2 (relationship between cognition and self-awareness), motor function was no longer significant after Holm correction, but cognition remained significant. Of note, having more anxiety symptoms significantly decreased the odds of impaired self-awareness (OR = 0.81, $p < 0.001$), but anxiety was *not* related to driving frequency nor restriction (all $p > 0.05$).

DISCUSSION

This study examined the relationships between cognition, self-awareness, and driving patterns (frequency and restrictions) among survivors of moderate-to-severe TBI who returned to driving. On average, survivors who resumed driving performed within the low average range on cognitive testing. Thirty-nine percent of survivors had impaired self-awareness of their cognitive function, which is consistent with the literature on self-awareness following moderate-to-severe TBI.[21] Individuals with better cognitive function were significantly less likely to have impaired self-awareness, while accounting for sociodemographic and medical factors. Specifically, for every 1 standard deviation increase in cognitive test performance, the odds of impaired self-awareness decreased by 97%. This supports prior findings that individuals with impaired self-awareness often have greater global cognitive deficits.[15,30] Additionally, better motor function significantly increased the odds of impaired self-awareness. This was surprising, as it was originally expected that individuals with better motor function would be less globally impaired and thus more likely to have intact self-awareness. On the other hand, the literature suggests that survivors of moderate-to-severe TBI are more likely to notice physical problems, while it is easier to miss and potentially ignore problems that are solely cognitive in nature.[10,16,22] In light of this, it is possible that individuals with better motor functionality (and thus no 'visible' impairments) were more likely to perceive themselves as overall intact (physically and cognitively), despite having cognitive problems. This raises the potential concern that survivors and caregivers may be making decisions about fitness to drive on the basis of survivors' physical function without considering their cognitive function. In the context of clinical care, these findings highlight the need for education about cognitive impairments after TBI to help increase awareness of the 'invisible' cognitive effects from injury.

Not only do a large proportion of survivors drive after their injury,[9] but the current findings show that the vast majority of survivors who resumed driving were driving frequently (i.e., 88% were driving numerous times per week). However, despite driving on a regular basis, survivors were not driving in *all* situations. On average, survivors described their driving as restricted in 6 out of 15 situations. Participants most frequently restricted their driving in unfamiliar areas (70%, n = 244), bad weather (62%, n = 216), when a map must be used (62%, n = 216), long distances (54%, n = 190), in heavy traffic (54%, n = 188), and at night (46%, n = 160). Furthermore, the situations survivors drove in differed based on their cognition function. Specifically, for every 1 standard deviation increase in cognitive performance, survivors restricted their driving in 1 less situation. This suggests that individuals with more cognitive deficits were perhaps hesitant to drive in certain situations. In other words, rather than ceasing to drive altogether, survivors may be compensating by restricting their driving in situations that are cognitively challenging for them. While it may be true that non-TBI drivers also limit their driving in the abovementioned situations, TBI drivers likely do so more than non-TBI drivers (especially since cognition impacts restriction), but future research should compare driving practices in TBI and non-TBI samples. Of note, urban-rural location was *not* significantly related to restricted driving, suggesting that cognition played an important role in determining survivors' driving patterns over and above differences in transportation based on area of residence. Overall, the findings illustrate how driving after moderate-to-severe TBI is not a unitary phenomenon. It is not merely a question of whether survivors are driving or not. Rather, survivors seem to be driving in some situations but not others. Thus, a more comprehensive approach to assessing and understanding driving after moderate-to-severe TBI is necessary. Given the tremendous impact driving has on daily function, assistance with return to driving decisions (e.g., how to resume driving, which situations to avoid due to cognitive weaknesses) should be emphasized in treatment planning and clinical care. Resuming driving, even in a restricted capacity, may allow a survivor to maintain a greater level of independence that substantially benefits their daily function. Thus, clinicians should incorporate personalized recommendations for gradual return to driving, potentially through the development of restricted driving plans that account for cognitive weaknesses.

While cognitive function impacts the situations survivors drive in, surprisingly, cognitive function was not related to how frequently they drive. This finding is consistent with the only other known study to examine cognition and driving frequency. Specifically, Gooden et al. found that neuropsychological measures of processing speed, attentional switching, visual perception, response inhibition, and planning were *not* related to changes in driving frequency after TBI,[14] although the study was limited by a small sample, shorter duration of recovery (≤ 3 years after injury), and exploratory correlation analyses. Gooden et al. also found significant correlations for sex and anxiety with driving frequency, whereby females and individuals with more anxiety tended to drive less frequently,[14] although the current study did *not* find differences in driving frequency based on sex nor anxiety. In a similar study that looked at average miles driven each week (i.e., a similar behavior to driving frequency), Coleman et al. found that cognitive function was *not* significantly related to miles driven among survivors of moderate-to-severe TBI.[6] Taken together, while survivors may be restricting their driving in certain situations possibly associated with cognitive difficulties, these restrictions may not limit how often they have the opportunity to drive. Additionally, survivors may be involved in activities that routinely necessitate driving (e.g., work, grocery shopping), thus driving frequently (even short distances) may be essential regardless of their cognitive status.

In the current study, self-awareness did not mediate the relationships between cognition and driving patterns. Self-awareness has been shown to impact driving performance via on-road driving evaluation, although studies were limited by small samples.[26,30] The current results suggest that self-awareness of cognitive deficits does *not* explain differences in driving restrictions over and above the influence of cognitive function. Prior research has shown that survivors of TBI with intact self-awareness were more likely to be drivers compared to those with impaired self-awareness.[6] Given that the current sample only included drivers, it is possible that participants all had a minimum requisite level of cognitive ability to operate a vehicle.[30] Therefore, individuals with the most severe cognitive impairment and potentially impaired self-awareness may have been selected out, which may have contributed to the nonsignificant findings. Another possible explanation is that survivors' driving patterns are dictated by externally-imposed restrictions more than self-imposed restrictions.[6,30] In other words, caregivers may be deciding if survivors are allowed to drive and setting the rules as to *when* survivors can and cannot drive. If caregivers are monitoring survivors' driving practices, then survivors do not need to rely on their own self-awareness to self-monitor their driving practices.[30]

Self-Awareness Sensitivity Analyses

The overall findings were relatively robust and sensitivity analyses did not lead to any significant changes in the role of self-awareness in driving. However, there is a lot of variability in how self-awareness is measured in the literature (e.g., self-report compared to objective report vs. physician report versus family report), and there is no established gold standard for measuring self-awareness after TBI.[21] The wide range of rates of impaired self-awareness reported in the TBI literature is likely in part due to the variability in samples and methods for measuring the construct. Moving forward, it will be important to arrive on a consistent definition for what is accepted as a measure of self-awareness. A standardized measure of self-awareness should be prioritized in future studies, rather than a study-specific method. Specifically, in the present study, the FIMCog items did not map onto the BTACT subtest domains perfectly, so it may not have been an optimal comparison for determining if there was a discrepancy between survivors' subjective self-reported cognition and their objective cognitive performance. More precise measures of self-awareness should be prioritized in future studies.

Strengths and Limitations

The present study examined the impact of cognition on driving practices after TBI, which has been sparsely researched to date. Additionally, this study involved a large, multi-center sample of participants who sustained a moderate-to-severe TBI, which allowed for greater generalizability of results. However, there are also limitations to this work. First, the sample is limited to individuals who self-identified as white or Black, so the results may not generalize to individuals of other races. Future studies with more racially diverse samples are necessary. Second, individuals with incomplete data (and thus excluded from the sample) were more cognitively impaired, more likely to have impaired self-awareness, and had less income compared to participants with complete data. These differences are a limitation of this work, as the results may not generalize to survivors with very severe impairments in cognition and self-awareness. Fortunately, the current sample still had a relatively even distribution across income categories, but further research on driving practices among survivors of low income groups is still warranted. Third, the cross-sectional design of this study limits interpretation of driving practices across recovery. This study showed that restriction of driving decreases as time since injury increases, suggesting survivors may resume driving in a slow, measured fashion and reduce restrictions over time (as practice and confidence increases). Longitudinal studies examining how driving practices and factors that impact driving practices (e.g., cognition) change over recovery are needed.

Future Directions

In light of the relatively sparse literature on driving practices after moderate-to-severe TBI, additional research is warranted to better understand factors that influence how frequently survivors drive and the types of situations they drive in (as well as those they avoid). It is possible that the dichotomization of driving frequency in the present study (due to low endorsements on several response options) reduced power to detect an effect, so future studies should aim to use a continuous measure of frequency. Furthermore, the current study focused on self-awareness of cognitive function, thus future research should examine other domains of self-awareness. In particular, it will be useful to address whether self-awareness of driving ability mediates the relationship between cognition and driving patterns. More research is also needed to better understand the impact of physical functionality on awareness of cognitive disturbances and driving. Studies should aim to gain a clearer understanding of what primarily informs driving decisions. For example, decisions may be based on the results of formal evaluation (e.g., neuropsychological evaluation, on-road driving evaluation), caregivers' appraisals, survivors' physical function, or survivors' cognitive function, and so on. It will be particularly important to determine if survivors and caregivers are making driving decisions predominantly on the basis of survivors' physical fitness without considering their cognitive fitness. Increased access to formal driving evaluation and development of driving services are paths to promote informed driving decisions following TBI. Given that driving is such a critical activity of daily living for functional success, promoting return to driving should be a key rehabilitation focus. Ultimately, more research is needed to gain a better understanding of safe compensatory strategies within the context of driving and to develop driving rehabilitation programs for survivors of moderate-to-severe TBI.

Conclusion

Most survivors who return to driving after their injury are driving frequently, but the situations they drive in differ based on their cognitive ability. Having more cognitive deficits is associated with increased restrictions in driving, even though driving frequency does not change. Driving after moderate-to-severe TBI extends beyond the question of whether or not a survivor drives a vehicle. Future research needs to focus on how cognition affects more nuanced aspects of driving behavior post-injury (i.e., which types of situations survivors drive in). The present findings also offer preliminary support that survivors are potentially compensating for cognitive deficits by restricting driving in certain situations. Future research examining compensation strategies in the context of driving after moderate-to-severe TBI is necessary to inform the development of driving rehabilitation programs to assist survivors with returning to drive after injury. By assisting survivors in driving again (and thus eliminating barriers due to lack of transportation), survivors will be more able to return to valued activities and productive roles.

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CONCLUSIONS

The overarching objective of this dissertation was to examine cognitive function and return to driving after sustaining a moderate-to-severe TBI, while also exploring the unique contributions of sociodemographic and medical factors. This was achieved through three papers with the following aims: (1) create a normative sample for the BTACT; (2) examine the relationship between cognitive function (memory and executive function) and return to driving after TBI; (3) examine the influence of cognition and self-awareness on driving patterns (frequency and restriction) following TBI.

In summary, the BTACT normative data were created from a national sample of 6,747 English-speaking healthy adults based on age, sex, and education. Consistent with other cognitive measures, BTACT scores decreased with age and increased with education. Among the sample of 585 survivors of moderate-to-severe TBI, 70% were driving at the time of cross-sectional follow up. Better performance on measures of verbal memory and executive function increased the odds of driving after moderate-to-severe TBI. However, the effects of cognition on driving status washed out when income and motor function were taken into account. Survivors with higher income and greater independence in motor function were more likely to be driving. Higher income and better motor function were also associated with better memory and executive function. Among the sub-sample of survivors who were driving, on average, overall cognitive performance fell in the low average range, and 39% of individuals had impaired self-awareness of their cognitive function. Survivors with more cognitive impairment and better motor function were more likely to have impaired self-awareness. The majority of survivors who resumed driving were driving frequently, but survivors were not driving in all situations. Individuals with more cognitive deficits restricted their driving more, but their driving frequency did not change (i.e., they still drove frequently).

These findings have a number of implications for clinical care and future research. First, the normative BTACT data facilitates assessment of cognitive function in future research studies by allowing for performance-based comparisons between survivors of TBI and healthy adults of the same age, sex, and level of education. The BTACT is a validated telephone-administered brief cognitive test battery, making it valuable for large-scale longitudinal research studies looking at cognition. Among survivors of TBI who have not returned to driving, telehealth cognitive testing offers a solution to the primary barrier of transportation to the testing site. This is the only known study to examine cognition and driving after TBI using telehealth cognitive testing. By eliminating in-person testing barriers, the present findings may be more representative of the overall TBI population compared to prior studies of cognition and return to driving.

Verbal memory, executive function, family income, and independence in motor function are barriers to driving after moderate-to-severe TBI. Survivors with family income < $25k and motor limitations are particularly at risk for not being able to return to driving. Clinically, it is important to keep these factors in mind when seeing patients. Tailored education about cognitive barriers to driving should be provided to survivors and caregivers. Additionally, future research should aim to parse out the specific mechanisms of why income and motor function are barriers to driving.

Furthermore, the issue of driving after TBI extends beyond the question of whether or not a survivor returns to driving a vehicle. A large proportion of survivors drive after injury and most drive regularly. Therefore, future research also needs to focus on how cognition affects more nuanced aspects of driving behavior post-injury (e.g., the types of situations survivors drive in). Survivors may be compensating for their cognitive deficits by restricting their driving in certain situations. Research examining compensation strategies in the context of driving after moderate-to-severe TBI is needed to inform the development of driving rehabilitation programs that assist survivors with returning to drive after injury.

Lastly, the role of motor function in both return to driving and self-awareness of cognitive function needs to be further explored. The present findings raise concerns that survivors are more focused on their ‘visible’ physical function, while their ‘invisible’ cognitive deficits are less likely to be identified and considered. Education to both patients and caregivers about cognitive impairments after TBI and risks for driving is necessary to increase awareness of the ‘invisible’ cognitive effects from injury. Increased access to professional consultation, including formal neuropsychological evaluation and on-road driving evaluation, is also important to help identify cognitive risks to driving and guide families in making informed decisions about returning to drive.

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APPENDIX

IRB APPROVAL FORM

THE UNIVERSITY OF
ALABAMA AT BIRMINGHAM
Office of the Institutional Review Board for Human Use

470 Administration Building
701 20th Street South
Birmingham, AL 35294-0104
205.934.3789 | Fax 205.934.1301 |
irb@uab.edu

APPROVAL LETTER

TO: DiBlasio, Christina A

FROM: University of Alabama at Birmingham Institutional Review Board
Federalwide Assurance # FWA00005960
IORG Registration # IRB00000196 (IRB 01)
IORG Registration # IRB00000726 (IRB 02)
IORG Registration # IRB00012550 (IRB 03)

DATE: 25-May-2021

RE: IRB-300007273
IRB-300007273-001
Cognition, Self-Awareness, and Driving After Moderate-to-Severe Traumatic Brain Injury

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The IRB reviewed and approved the Initial Application submitted on 16-Apr-2021 for the above referenced project. The review was conducted in accordance with UAB's Assurance of Compliance approved by the Department of Health and Human Services.

Type of Review:	Exempt
Exempt Categories:	4
Determination:	Exempt
Approval Date:	25-May-2021
Approval Period:	No Continuing Review

The following apply to this project related to informed consent and/or assent:

- Waiver of HIPAA

Documents Included in Review:

- IRB EPORTFOLIO
- IRB PERSONNEL EFORM

To access stamped consent/assent forms (full and expedited protocols only) and/or other approved documents:
1. Open your protocol in IRAP.