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Driving Through The Fog: The Impact Of Traumatic Brain Injury On Mental Fog And Driving Performance

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DRIVING THROUGH THE FOG: THE IMPACT OF TRAUMATIC BRAIN INJURY ON MENTAL FOG AND DRIVING PERFORMANCE

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LIFESPAN DEVELOPMENTAL PSYCHOLOGY PROGAM

ABSTRACT

Every year, millions of people in the United States sustain a traumatic brain injury (TBI). Subsequently, a subset of people with TBIs may incur roadway crashes due to poorer vehicle maneuvering and problems with higher-order driving skills such as speed control and lane maintenance. Research is needed to better understand what relates to driving aptitude following TBI. Previous research in individuals with TBI has focused on objective cognition, the set of mental abilities that help to process information for memory, planning, and action. TBIs can result in cognitive difficulties, which for some, may last months after mild cases and a lifetime after moderate-to-severe TBIs. To date, most studies have used performance on cognitive tasks (i.e., objective cognition) to predict driving ability after TBI, finding that lower cognitive ability related to poorer on-road and simulated driving ability. An emerging line of research shows that subjective cognition may additionally predict poor driving after TBI. One subjective cognitive complaint after TBI is the metacognitive awareness of mental fog, or problems with cognitive processes accompanied by mental clutter. The current study expanded this research by examining whether subjective cognitive difficulty and cluttered thought can predict simulated driving performance in a cross-sectional evaluation of individuals who have sustained mild and moderate-to-severe TBI. Findings illustrated higher mental fog in mild TBI compared to healthy controls although not significantly different from moderate-to-severe cases. Mental fog was unrelated to cognitive performance after mild TBI but linked to disrupted updating and slowed processing speed after moderate-to-severe TBI. Regarding primary outcomes, higher mental fog corresponded to more self-reported driving difficulties after mild TBI and faster average speeds after moderate-to-severe TBI. Subjective cognition, thus, appears relevant to safer driving after TBI alongside objective cognitive performance. After injury, assessing mental fog may be beneficial in identifying those less likely to return to drive and whom require training or rehabilitation.

Keywords: driving, traumatic brain injury, concussion, cognition, subjective cognition

DEDICATION

"I must not fear. Fear is the mind-killer. Fear is the little-death that brings total obliteration. I will face my fear. I will permit it to pass over me and through me. And when it has gone past I will turn the inner eye to see its path. Where the fear has gone there will be nothing. Only I will remain." – Frank Herbert, Litany Against Fear

This work is dedicated to my father, Lance Bell, who always repeated this quote to me as a kid. I may have not understood the meaning as a child but as I get older the relevance clears. Unless we face fear head on, fear hurts or destroys that and those we care for. I attempt to apply this mantra to my studies, teaching, and relationships – though, honestly, not an easy task. Secondly, I dedicate this work to my mother, Sherry, who taught me to take life day by day and to find humor in dark times. I also dedicate this work to my late grandmother, Dorothy Darnell, a beacon of compassion and kindness who corrected my course several times. Despite being different and coming out, she showed that love was Godlier than judgement. Furthermore, I dedicate this work to my Super Sisters, Brittany and Erica, who always looked out for me and now do the same for their own beautiful children. My nieces and nephews could not be luckier to have such loving and smart mothers. I owe further gratitude to Caitlin, for being my courage, Hang, for being my happiness, and James for being my joy. Lastly, I dedicate this work to my twin, Coby, who I eternally love and believe in.

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Lastly, I thank all the participants who provided their time to complete the studies. I believe that the TRIP Lab's work will produce translational outcomes that will improve the lives of individuals at greater crash risk, especially as the simulator becomes utilized for clinical decision making and training.

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CHAPTER 1

INTRODUCTION

Every year, 1.7 million people in the United States suffer external, kinetic force to the brain altering function and creating pathology known as traumatic brain injury (TBI; Menon, Schwab, Wright, & Maas, 2010). This condition is appreciable with an increase of 150% more cases diagnosed in 2010 as compared to 2001 (CDC, 2014). This jump likely denotes increased awareness of TBI among healthcare providers and the public (Taylor, Bell, Breiding, & Xu, 2017). Still, these numbers underestimate true prevalence of TBI as most cases are mild and never receive medical attention. Meanwhile, fatalities related to TBI decreased over this period, likely due to better post-traumatic monitoring (Gerber, Chiu, Carney, Härtl, & Ghajar, 2013) and other medical advances (Carney et al., 2017). As individuals with TBI survive and live longer, the focus evolves to the prevention of cumulative injuries, such as future motor vehicle collisions (MVCs), one of the leading causes of death across the lifespan (Webb, 2018) and after TBI (Harrison-Felix et al., 2012; Ventura et al., 2010).

The major categorizations of TBI severity include mild and moderate-to-severe. Mild cases are most frequent, accounting for nearly 90% of all reported incidents (Ruff, 2011). Primary causes for minor injuries include falls (60%), sports activity (30%), and MVCs (25%; CDC, 2017; Gaw & Zonfrillo, 2016). The American Congress of Rehabilitation Medicine defines mild TBIs as injuries that exhibit one of four main symptoms: (1) any period of lost consciousness, lost memory, altered mental state, or any neurological deficit after injury (2) loss of consciousness <30 minutes, (3) posttraumatic amnesia < 24 hours (4) score of 13 to 15 on the Glasgow Coma Scale. The Glasgow Coma Scale is a routine assessment of consciousness quantified by responses to motor, verbal, and eye-opening ability, ranging from a score of 3 to 15 points with lower scores indicating lower consciousness (Jones, 1979). Other than these criteria, mild TBIs are invisible to modern neuroimaging and have weak to modestly sensitive biomarkers (Blake, Gonzalez, & McMahon, 2018; Fiandaca et al., 2018), constraining clinicians to rely mostly on self-reported post-concussive symptoms and professional judgement. Such symptoms encompass somatic (headache, noise sensitivity), emotional (e.g., irritability, depressed mood), and cognitive struggles (e.g., memory loss, fogginess) that can discriminate persons who are injured from non-injured (d = 1.24; Lovel et al., 2006). Objective metrics of mild TBI include subnormal tandem gait (Vanderploeg, Curtiss, Luis, & Salazar, 2007) and processing speed (Mathias, Beall, & Bigler, 2004) that can be useful to quantify severity and monitor recovery (Iverson, Grant, Lovell, & Collins, 2005; Sheedy, Harvey, Faux, Geffen, & Shores, 2009).

The other 10% of TBIs are moderate to severe (Ruff, 2011). The most common causes of moderate-to-severe TBIs, determined by required hospitalization, was predominantly falls (50.4%) and MVCs (21.5%, Taylor, Bell, Breiding, & Xu, 2017). Such cases comprise head injuries with lost consciousness >30 minutes, post-traumatic amnesia >24 hours, and Glasgow Coma Scale less than 13. Unlike milder forms, many moderate-to-severe TBIs exhibit focal and diffuse brain damage seen through neuroimaging that explain observable symptoms (Povlishock & Katz, 2005). Such observable symptoms after moderate-to-severe TBI encompass deficits in motor skills (e.g., ataxia, paresis, postural instability; Walker & Pickett, 2007), psychological function (e.g., major depressive disorder, substance use disorder, organic personality syndrome, panic disorder; Koponen et al., 2002) and cognition (executive dysfunction, slow cognitive speed, inattention; Mathias, Jane, Wheaton, 2007).

Across severities, TBI impedes cognition, or the mental processes necessary for goal-directed behaviors such as safely navigating a driving environment. Specifically, TBI results in slower cognitive speed, inattention, memory disorder, as well as problems with executive functions such as planning, organizing, set-shifting, and updating for goal behavior (Mcallister, Flashman, Sparling, & Saykin, 2004; Rao & Lyketsos, 2000; Ross et al., 2014; Stuss et al., 1989). These processes help us to safely operate a vehicle, navigate roadways, and maneuver through traffic. For example, faster processing speed and focused attention help drivers quickly react to hazards (Schulthies et al., 2010). Meanwhile, better memory and updating (keeping relevant information in working memory) minimizes roadway violations and lane deviations, respectively (Mäntylä, Karlsson, & Marklund, 2009; Schulthies et al., 2010). Being able to learn and control cognition contributes to driving proficiency; harm from injury may therefore interject safe car operation.

In addition, many people with TBI experience subjective cognitive impairment, or the metacognitive perception that they fail mental tasks. Despite impaired awareness, 30 to 40% of individuals with mild or moderate-to-severe TBI report some form of subjective cognitive impairment (e.g., forgetfulness and inattention; de Boussard et al., 2005; Hart, Whyte, Kim, & Vaccaro, 2005). While negative affectivity can generate this perception (Spencer, Drag, Walker, & Bieliauskas, 2010), insights might reflect real-world cognitive failures relevant to driving. As described below, there is substantial evidence that metacognition can describe issues in cognition (Chamelian & Feinstain, 2006; Schiehser et al., 2011) as well as car operation and navigation (Kass, Beede, & Vodanovich, 2010; Pope, Ross, & Stavrinos, 2017; Wickens, Toplack, & Wiesenthal, 2008) but little research explores this after TBI (Rike et al., 2010). To fill critical gaps in this content area, the goal of the current study is to examine how subjective cognition predicts driving performance after TBI over and above scores on objective cognitive tasks. Specifically, we explored the role of mental fog or the subjective cognitive impairment accompanied by a lack of mental clarity (Katz et al., 2004; Theoharides, Stewart, Hatziagelaki, & Kolaitis, 2015).

Mental Fog

Mental fog appears optimum to capture subjective cognitive experiences after TBI. Specifically, mental fog is the offline metacognitive monitoring of general cognitive impairment accompanied by a lack of mental clarity (Katz et al., 2004; Nelson & Esty, 2015; Theoharides, Stewart, Hatziagelaki, & Kolaitis, 2015). Offline monitoring means that perceptions of mental fog come from declarative knowledge and a decoupled view of oneself rather than judgments during active tasks (i.e., online monitoring). This symptom mirrors “clouding of consciousness” in delirium research (Schuurmans, Shortridge-Baggett, & Duursma, 2003), described by the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2000) as trouble focusing, sustaining, or shifting attention, and reduced clarity in awareness. Likewise, individuals with mental fog experience unclear cognizance attended by forgetfulness, inattention, trouble multitasking, and slowed thinking; however, this does not adopt the psychotic symptoms of delirium. Previous metacognitive constructs typically capture one domain such as memory (e.g., Multifactorial Memory Questionnaire; Troyer, & Rich, 2002) or fail to quantify clouding of consciousness (Cognitive Failure Questionnaire; Wallace, 2004). The construct of mental fog resolves these limitations and serves as a global measure of subjective cognition to examine with driving behavior.

Mental fog appears escalated by disease or pathogen rather than a normal cognitive attribute, supporting discriminant validity as an illness symptom (Jackson & Hassard, 2016; Theoharides, Stewart, Hatziagelaki, & Kolaitis, 2015). For example, persons with chronic pain report higher mental fog (50.9%) than healthy controls (8.8%) captured by coincident complaints of forgetfulness and mental confusion (Katz, Heard, Mills, & Leavitt, 2004). Secondly, 85% of adults with chronic fatigue describe problems with confusion and hazy thinking in addition to general cognitive issues (e.g., slowed thinking and inattention; Komaroff, 1993). Corresponding to dwindled cognitive performance, 67% of individuals with postural tachycardia syndrome reported mental fog primarily described as forgetfulness, cloudiness, or difficulty focusing (Ross, Medow, Rowe, & Stewart, 2013). Neurotoxicity and pathogenic inflammation also produce mental fog: For example, 70% of side effects from chemotherapy involve cognitive fogginess (Boykoff, Moieni, & Subramanian, 2009). Severe reactions to subcutaneous immunoglobulin replacement are primarily characterized by clouded consciousness and mental confusion (Gardulf et al., 1995). Lastly, physicians find mental clouding as a common result of viral infection (Forton, Thomas, & Taylor-Robinson, 2004). Thus, while the concept of the mental fog is subjective and reliant on somewhat biased perceptions, it holds clinical relevance as a possible disease symptom.

As expected from an injury jolting mentation and consciousness, there are considerable fog-like symptoms after brain injury. In mild TBI, many researchers used one-item scales to assess this perception of “fogginess”, a part of the Post-Concussive Symptoms Scale (Lovell et al., 2006). As the most conservative estimate, Iverson, Gaetz, Lovell, and Collins (2004) found that 17% concussed athletes experienced fogginess greater than noninjured peers related to forgetful memory and slower cognitive speed. Later, Broglio, Sosnoff, and Ferrara (2009) found that 59.4% of athletes with concussion show poor concentration and fogginess that again produced forgetful verbal memory and slower reaction time. Duhaime et al. (2012) prospectively followed concussions in a large cohort of collegiate athletes. As the most common sequalae of incident concussion (n = 44), 36 (81.2%) complained of mental fog defined by feeling slowing thoughts, confusion, and “in a fog”. In fact, this symptom was more common than headaches (65.9%), dizziness (43.2%) or neck pain (25.0%). In addition to trouble remembering, individuals with mild TBI report greater “confusion” compared to uninjured peers (Vanderploe, Curtis, Luis, & Salazar, 2007). Though diminishing over time, Ponsford, Cameron, Fitzgerald, Grant & Mikocka-Walus (2011) reported that individuals with mild TBI reported fogginess two times greater than controls immediately after injury (60.0% versus 30.0%), one week later (40% versus 20%), and 3 months later (15.7% versus 11.3%). Mental fog is so pervasive in mild cases that the third International Conference on Concussion in Sport released a consensus that mental clouding was a key symptom of concussion in 2008 (McCrory et al., 2008). Although the American College of

Rehabilitation Medicine and World Health Organization Task Force already introduced disorientation or confusion as an important mental state after mild TBI earlier (Carroll, Cassidy, Holm, Kraus, & Coronado, 2004; Kay et al., 1993).

Few studies straightforwardly assessed mental fog after moderate-to-severe TBI though commonly discussed in the head injury community (Arms, 2013; Whittemore, 2016). Instead, most research captures "confusion" after moderate-to-severe TBI – nearly tantamount to clouded consciousness. For example, Stuss et al. (1999) described the early recovery period after lost consciousness as posttraumatic confusional state characterized by deficits in global cognition, attention, psychomotor activity, and disturbed cognizance. Stuss and colleagues (1999) argue that though post-traumatic amnesia remains a TBI hallmark, memory loss certainly does not fully describe the entire post-injury state. Indeed, during the acute injury phase 70% appeared in post-traumatic confusional states (assessed by the Confusion Assessment Protocol) which also corresponded to DSM criteria for delirium (Sherer, Nakase-Thompson, Yablon, & Gontkovsky, 2005). Being in this befuddled state predicted higher disability at rehabilitation discharge even after controlling for demographics (gender and age) and injury severity (Glasgow Coma Scale score and length of hospital stay). Severity of post-traumatic confusion also predicted lower likelihood to regain employment or productivity one year later. Moreover, signs of disorientation in posttraumatic confusional state predicted outcomes better than cognitive impairment alone, emphasizing the importance of both symptom clusters (Nakase-Richardson, Yablon, & Sherer, 2007). This is likely because residual confusion and subjective cognitive impairment persists after injury – despite recovered awareness – and collectively interfere with daily function.

Thus, research on “fogginess” and post-traumatic confused states suggest that mental fog, a combination of subjective cognitive problems and disoriented consciousness, may suitably predict real life outcomes. As one of the first inquiries on this topic, the current proposal examines how mental fog predicts driving – one of the most cognitively complex everyday behaviors – after mild to moderate-to-severe TBI. To accentuate the need for this study, we describe how many return to drive after TBI and evidence of greater crash risk therefrom. Next, we describe substandard driving and cognitive performance after TBI that may explain raised crash risk. Lastly, we discuss how objective and subjective cognition both predict driving outcomes. Altogether, this supports mental fog as a disruptor of driving performance after injury.

Driving after TBI

Returning to drive.

Independent driving is an important goal for those with TBI even when unable to do so (Rapport, Bryer, & Hanks, 2008). Returning to drive post-injury is clinically relevant as driving cessation can decrease one’s quality of life, mental health, life satisfaction, and community integration (Harrison & Ragland, 2003; Ragland, Satariano, & MacLeod, 2005; Rapport, Hanks, & Bryer, 2006). The strong desire for a return to independence and “normalcy” may result in driving among individuals who have persistent impairments in driving capabilities. The current proposal reviews rates of return-to-drive after TBI as well as the risk for unsafe driving outcomes after injury. This helps to emphasize that, although the desire to return to drive is high, individuals may not be aware of impairments in their roadway operation and their increased risk of crash-related injury. Thus, many persons may resume driving with ongoing disruptions in physical and mental function.

For mild TBI cases, more than 90% of individuals return to drive an average of one year post-injury (Bottari, Lamothe, Gosselin, Gélinas, & Ptito, 2012), but far fewer will return after moderate-to-severe cases. Specifically, 40 to 60% of those with moderate-to-severe TBI become active drivers again (operates a vehicle 7 days a week; Fisk, Schneider, & Novack, 1998; Pietrapiana et al., 2005; Priddy, Johnson, & Lam, 1990; Rapport et al., 2006) though rates increase with longer recovery duration (Novack et al., 2010). Using information from a nationally representative database of patients with TBI, Novack and colleagues (2010) found that of over 4,500 individuals with brain injury followed for 2 years, 42% returned to drive within that period. Of more than 2,300 individuals followed for 5 years, 53% returned to drive. Similarly, Formisano, Bivona, Brunelli, Giustini, Longo, and Taggi (2005) found that 32% of those with severe TBI returned to driving 5 years after injury. Thus, both cross-sectional and longitudinal observation shows that most will return to driving after mild TBI and a substantial portion will also return to driving after moderate-to-severe TBI.

Although the road to driving resumption is open for many TBI survivors, it does contain legal barriers that may account for lower rates of resumption in moderate-to-severe TBI (aside from greater symptoms). In a few states, physicians or patients can report conditions of lost consciousness to their state's Department of Motor Vehicles/Medical Advisory Board who review and may require physician approval and repeated driver testing (e.g., California Medical Association, 2012; Pennsylvanian Department of Transportation, 2018). Otherwise, most states leave the decision to the clinician on whether to report individuals who they believe should not drive. While mandated reporting is somewhat protective, such laws face poor adherence and can harm clinician-patient relationships (Elgar & Smith, 2017). Instead, many patients wait on clearance from their physician, typically upheld by cooperation with caregivers. Guidelines on return to drive after mild TBI are few (Bottari, Lamothe, Gélinas, & Ptito, 2012), which may explain high rates of resumption. Whether individuals who drive again are at high risk of collisions remains an important topic for clinicians who aim to keep clients and the community safe.

TBI and crash risk.

As many individuals with TBI return to drive, a major concern is whether they experience worse driving outcomes than peers due to enduring cognitive difficulties. Although many believe individuals with TBI are more likely to incur collisions after injury than noninjured peers, the evidence remains tentative.

Formisano et al. (2005) conducted one of the first studies on this topic. Researchers followed 90 people with severe brain damage, 80% of whom had TBI. Among the 29 (32%) individuals who returned to drive, a significant portion (n = 11, 45%), experienced an MVC after about 5 years since injury. Amongst the TBI group, persons incurring an MVC did not differ from those without an MVC on age, gender, or coma duration; though there was a significant difference on average time elapsed post-injury with those reporting MVCs having more roadway exposure since injury. Formisano et al. (2005) concluded that the MVC rate was 2.3 times larger than that for the normal population. Two methodological issues limit this finding, however: First, MVC rate was calculated over the total incidents in a 5-year span for the TBI group but only per year in healthy controls. Secondly, this study compared MVC rates from a very small TBI sample and compared it to epidemiological data which might be inappropriate.

Two studies then compared MVC rates with collected control groups. Schanke, Rike, Mølmen and Østen (2008) assessed risk of MVC among individuals with TBI compared to a clinical control sample (cerebrovascular disease [CVD]) and normative data. Researchers mailed questionnaires to patients evaluated for fitness to drive at a rehabilitation hospital. On average, the TBI group was surveyed 9 years after injury. Persons with TBI had driven a similar number of years (8.9 years), kilometers weekly (163.5 km), and daily drives (81.5%) compared to persons with CVD. From the TBI group, 15 persons reported being involved in an MVC, which is higher than expected from normative data (n = 6.25). Despite similar driving experience, the rate of MVC was 3 times higher for persons with TBI than persons with CVD, and persons with CVD were more likely to avoid driving (decreased exposure).

Similar results were found when looking at at-fault crashes (Bivona, D'Ippolito, Giustini, Vignally, Longo, Taggi and Formisano; (2012). Looking at 60 active drivers, Bivona et al. (2012) found that 19 (63%) were involved in an MVC post-injury. Of all the 62 crashes incurred by these individuals, and 36 (58%) were at-fault MVCs. Overall, persons with TBI who resumed driving had over two-fold greater odds of MVC after injury compared to before. Nonetheless, alongside Schanke et al. (2008), this study inspected small samples which obscures any conclusions to larger populations – especially for a low-base rate events like crashes.

In an attempt to compare larger samples, Neyens and Boyle (2012) cross referenced persons with TBI (occurring between 1995 and 2006) from the Brain Injury

Registry with crash records maintained by the Iowa Department of Transportation. The Brain Injury Database includes many mild TBI and severe TBI cases sustained between 1995 and 2006 with an average GCS of 12.6 (*SD* = 4.1). Researchers merged these data with crash records obtained between 2001 and 2006. Overall, 1,583 of those with TBI had at least one MVC post-injury. However, this study provided no data on the total of TBI cases followed from 2001 to 2006 making it impossible to compare MVC rates between injured and noninjured drivers. Instead researchers compared rates of having multiple MVCs out of all people with an MVC: Approximately 14% of those involved in one post-TBI crash were involved in multiple MVCs. This percentage is statistically higher than for persons without TBI in the crash database (10.4%). Predictors of multiple crashes included less post-injury time, younger age, and higher injury severity. The association with younger age may be explained by poorer on-road driving performance shown by younger survivors of TBI (Novack et al., 2006).

High risk of MVC after TBI is also shown in veteran populations Carlson, O'Neil, Forsberg, McAndrew, Storzbach, Cifu and Sayer (2016) used a national database to compare groups of veterans with and without TBI on subsequent risk of MVC-related hospitalization. Overall, 277,300 veterans enrolled with one year of deployment were identified, 10.3% of whom sustained a TBI. Of the total sample, 422 veterans were hospitalized for MVC-related injuries within five years of deployment and 31% of those veterans had a TBI diagnosis preceding the incident. Survival analysis indicated that veterans with TBI were 4.0 times as likely to be hospitalized for MVC-injury than those without TBI, after controlling for demographic factors (e.g., age, gender, race, education) and military differences (e.g., branch, number of deployments, miles to nearest VA hospital, service connection status). In addition, this study controlled for common psychiatric issues like PTSD that might inflate crash risk (Bullman & Kang, 1994).

Not all studies of TBI and crash risk show consistent results, however. Haselkorn, Mueller and Rivara (1998) failed to find an elevated risk of MVC among TBI using surveillance data. Four clinical cohorts were identified by merging state crash records with hospital discharge data, including persons with TBI and CVD, who were matched with nonhospital persons on age, gender, location. After adjusting for prior driving record, neither the TBI nor CVD group showed an inflated crash risk 12-months after discharge. However, there was an increased risk of driving violations for those with TBI compared to non-injured healthy controls (RR = 1.30). Recently, Ross, Ponsford, Di Stefano, Charlton and Spitz (2016) evaluated 207 persons with mild to severe TBI using on-road driving assessment and found no significant difference between the number of self-reported pre- and post-injury crashes among people with moderate-to-severe TBI. However, there were a significantly greater number of near-crashes after TBI for persons passing on-road driving assessments compared to pre-injury rates. Lack of differences between pre- and post-injury crashes may be due to driving restriction among participants who did not pass on-road assessment. They also found that those with shorter post-traumatic amnesia (PTA), and no physical or visual impairment were more likely to pass the on-road driving test. Injury severity measured by the Glasgow Coma Scale (GCS), however, was not significantly predictive of passing or failing the driving test. In addition, drivers with TBI who reported crashes were comparable to drivers who did not report a crash on age at injury, age at study, TBI severity (post-traumatic concussion symptoms and PTA duration) or gender proportion.

Altogether, the literature remains unclear on how crash risk changes after TBI. A recent meta-analysis of these studies further exemplified this confusion. Chee et al. (2008) found that although s shown before, studies are either small in sample size or include nonrepresentative control groups. A recent meta-analysis conducted by Chee et al. (2018) noted these limitations.

Driving performance.

Troubles in driving performance after TBI might make some individuals more prone to collisions. This has been shown in other populations like younger and older adults. For example, 79.3% of all teen crashes involved on-road driving errors such as problems with visual attention (46.3%) or problems in driving too fast or following cars to closely (40.1%; Curry, Hafetz, Kallan, Winston, & Durbin, 2011). Meanwhile, simulated problems in speed control retrodicted prior crash events in older adults (Lee, Lee, Cameron, & Li-Tsang, 2003). Substandard driving might likewise elevate crash proneness after TBI. Indeed, several studies find differences between on-road and simulated driving between participants with TBI and healthy counterparts.

On-road driving performance.

On-road driving assessment is considered the gold standard in deciding fitness to drive after brain injury (Classen et al., 2009) and has been used over the last thirty years to spot unsafe driving behaviors. One of the earliest studies was conducted in 1981 by Sivak, Olson, Kewman, Won and Henson (1981) with a group of participants with "brain damage" including severe concussion (*n* = 23), a group of participants with spinal cord injury (*n* = 8), and healthy participants (*n* = 10). All groups were mostly male (50%-

72%), the stroke and spinal cord injury groups were mostly young adults and the brain damage group was more middle-aged. Along with completing several cognitive-perceptual tasks, all participants completed a closed- and open-course driving assessment with a licensed driving educator. The driving educators assessed gap acceptance, correct stopping and yielding, observational behavior (checking mirrors prior to turns/lane change), lane deviation, and speed. Overall, persons with brain damage showed greater lane deviation on turns, worse ability to take a safe gap acceptance, and lower driving capacity overall compared to healthy controls. This was also shown in comparison to a clinical control group (i.e., individuals with spinal cord injury).

Stokx and Gaillard (1986) used an instrumented vehicle to assess people with TBI (*n* = 13). This group had sustained an MVC-related concussion with a coma lasting 1 to 8 weeks (likely severe TBI), was young, showed no neurological deficits on sensory or motor skills, had normal vision, and were licensed drivers or in driver training. Adults with TBI were matched with 13 healthy participants on age, gender, and years of education. Using a closed course, researchers measured the participants' ability to shift gears, accelerate and decelerate, time needed to come to a full stop, distance from line, brake irregularities, and ability to drive through/around cones with and without secondary task distraction. Though they did not exhibit significantly more driving errors than healthy controls, participants with TBI took significantly longer to complete most tasks including shifting gears, braking, and driving around cones with and without distraction. Prior to the driving assessment, all participants completed a reaction time test that involved pressing a button as fast as possible when a light went off above it. Slower reaction times significantly associated with decreased ability to drive around cones in the

TBI group. Although individuals with TBI did not show obvious sensory or motor deficits, the experiment provided evidence that they may be at-risk drivers due to a general slowing in reaction time during driving performance.

These observational (somewhat naturalistic) studies suggest more unsafe driving after TBI. Specifically, among closed and open-course settings, participants with TBI show greater variability in lane position on straight and curved roads compared to healthy and clinical controls (i.e., spinal cord injury; Sivak et al., 1981), suggesting problems with lane maintenance. They also show slower brake times indicating problems in speed control (Stokx &Gaillard, 1986). More so, participants with TBI take longer to complete operations such as gear shifting, making left-hand turns in oncoming traffic, and maneuvering around obstacles (Sivak & Gaillard, 1986; Sivak et al., 1981). Such errors and difficulties appear to involve slower speed rather than not knowing appropriate procedures – which ultimately leads to lower ratings from instructors. One limitation of such studies is that they cannot ethically test driving performance under risky, but common, conditions such as distracted driving nor examine responses to safety critical events (oncoming car, pedestrians walking on road, parallel car spontaneously merging into lane). Thus, driving simulators emerge as a useful tool to measure such situations while objectively estimating driving performance.

Simulated driving performance.

Driving simulators show promise for evaluating driving behavior of individuals with TBI in a safer, controlled environment. Liu, Miyazaki and Watson (1999) studied simulated driving behavior among community dwelling adults with sustained head-injury (*n* = 17) and uninjured peers (*n* = 17) matched on gender, age, and years of education. A virtual reality simulator tested participants on a variety of driving behaviors. Group comparisons showed that those with acquired head injury performed worse at backing out of a driveway, merging into traffic, changing lanes, and avoiding traffic. Participants with head injury also crossed the centerline more often that non-injured participants while following traffic, driving on curved roads, and when there was traffic in the opposite lane. They also crossed the shoulder line more often among these same scenarios, indicating a poorer ability to maintain lane position. Lastly, participants with head injury made a greater number of incorrect stops. Interestingly, when participants were asked to rate their driving ability, those with head-injury rated their driving ability similarly to the healthy controls. Thus, simulated driving performance may be more indicative of true ability as compared to self-report in determining driving ability post-injury.

In an effort to validate discriminate validity of driving simulators, Lew, Poole, Lee, Jaffe, Huang and Brodd (2005) assessed driving performance among TBI survivors referred from a local driving evaluation program (*n* = 11) and a group of healthy adults (*n* = 16) matched on average age and gender proportion. The TBI sample consisted mostly of younger adult males tested 8 months after injury. Participants completed a driving evaluation including on-road and simulated drives. For the on-road testing, a professional driving instructor using the Driving Performance Index (DPI) evaluated participants. The DPI recorded a person's ability to handle controls, regulate trajectory, perform basic maneuvers, and use higher-order skills to make safe decisions and control emotions. Persons failed the DPI assessment if they got a score lower than a set cut-off or displayed one episode of reckless driving. Participants then completed a simulated drive using a 21-inch color monitor with speakers, a mounted steering wheel, accelerator and brake pedal. This simulator obtained information on measures of speed variation and speed violations, lane position and variability in straight and curved roads, steering behavior, and number of MVCs. The simulator produced an overall Simulator Performance Index (SPI) score, a standardized composite score of driving ability, with higher scores indicating better driving. Overall, participants with TBI performed worse on the DPI and the SPI (d = 2.14 and 1.53, respectively) compared to healthy controls. Compared to normalized reference scores, persons with TBI did worse on measures of speed control including percent of time exceeding posted speed limits, greater speed variability, and acceleration variability. They also showed poorer direction control including worse lane position and variability on straight roads, steering jerks, high number of collisions, and off-road deviations. Thus, simulated performance indicated worse driving performance in TBI compared to healthy individuals, similar to the results provided by the on-road assessment.

Cyr, Stinchcombe, Gagnon, Marshall, Hing and Finestone (2009) assessed crash rates between persons with TBI compared to uninjured individuals. Participants were recruited through a local rehabilitation center, tested around 6 years after injury, had a valid driver license, and had no significant motor impairment required for vehicle operation. Most of the participants had moderate-to-severe TBI as measured by the GCS and had PTA lasting over 48 hours. All participants underwent simulated driving using a projected environment and an apparatus equipped with a steering wheel, brake, accelerator, blinker, and odometer with three rearview mirrors. Each participant drove on a two to four lane road within a suburban environment with cross traffic, oncoming traffic, and pedestrian traffic. Four hazards were embedded into simulated scenarios including a car incursion at an intersection, pedestrian crossing, a car in oncoming traffic crossing the centerline to pass, and an incursion from a parked car. Overall the individuals with TBI had a higher average number of crashes than the healthy controls ($d = .68$). Simulated assessment allowed prediction of MVC risk directly using embedded hazards, not ethically possible for on-road assessments.

Driving simulators provide a means to reveal visual scanning differences between individuals with TBI and healthy peers. Milleville-Pennel, Pothier, Hoc and Mathé (2010) assessed eye movements during simulated driving behavior among a small sample of males with TBI ($n = 5$) and healthy male peers ($n = 6$). Participants with TBI had severe scores indicated by a GCS lower than 8 with at least 48 hours of coma duration ($M = 13$ days, range = 8 to 18 days) and averaged 12 years post-injury (range = 10-15). The driving simulator in this study was equipped with an automatic gearbox, steering wheel, brake, accelerator and speedometer with a visual projection of the road environment. In addition, a head-mounted eye-tracker was used a capture participant eye movements and field of view. Participants completed driving scenarios which increased by the number of other-road users (pedestrians, oncoming traffic, following traffic). The average eye fixation was higher for participants with TBI during straight road conditions ($d = .98$), but not for curves. There was also marginal evidence that persons with TBI attended less to mirrors on straight road segments compared to healthy controls. Therefore, it appears that drivers with TBI explore less of the visual field and focus more on the immediate task of lane management. This lack of visual exploration towards peripheral fields may place TBI survivors at risk of MVC-related injury, as inability to divide attention is predictive of at-fault MVCs (Ball et al., 2006).

With most of the driving performance evaluations occurring for moderate-to-severe TBI, it should be noted that riskier driving performance is also shown in cases of mild TBI. Classen, Levy, Meyer, Bewernitz, Lanford and Mann (2011) recruited veterans diagnosed with mild TBI or post-traumatic stress disorder from a local Veterans Affairs hospital and healthy adults from local registries to evaluate driving ability. This is especially relevant as mild cases accounted for 81% of all TBI cases in 2010, and many veterans with mild TBI will not receive medical attention (Fischer, 2014), thus returning to driving without formal evaluation. All participants completed simulated driving using an apparatus (a car cab) equipped with side view mirrors, a steering wheel, accelerator, brake pedal, and realistic audio sounds. The driving simulation involved a projected environment with 180-degree visual field. Overall, veterans with brain injury showed more excessive speeding, lower use of signaling, and poorer adjustment to stimuli compared to healthy controls. There was marginal evidence that veterans with mild TBI required greater time for gap acceptance compared to healthy controls. However, it should be noted that the healthy controls were slightly older and consisted of more females than the TBI group. As males generally demonstrate more risky driving behavior (Oltedal & Rundmo, 2006), conclusions from this study may require caution.

More recently, Schmidt, Hoffman, Ranchet, Miller, Tomporowski, Akinwuntan and Devos (2016), examined driving behavior within 48 hours of symptom resolution among college students who sustained mild TBI. Participants completed symptoms assessment, neuropsychological assessment, and a simulated drive. The simulated driving included a desktop computer simulation with 145-degree field-of-view with a steering wheel, accelerator, and brake pedal. Participants drove a 20.5 km scenario with a varied environment. The scenario included traffic with urban, suburban and rural settings, straight and curved roads, two- and four-lane roads, cross walks, and various speed limits. Hazards were embedded in the scenario. Compared to healthy controls recruited from the community, participants with mild TBI had greater lane excursions, greater variability in lane position at smooth and sharp curves, and greater speed variability at the final left curve of the scenario. Thus, even after symptom resolution, participants with mild TBI showed more unsafe driving behaviors.

Alongside on-road testing, simulators provide insight into driving disruptions in TBI. First, simulators with embedded hazards showed that months and years after moderate-to-severe TBI, survivors are at greater odds of hitting other cars and pedestrians (Cyr et al., 2009; Lew et al., 2005); more work is needed to evaluate simulated crash risk in mild TBI (Schmidt et al., 2016). Additionally, simulators validate instructor-rated problems in lane maintenance and speed control. Regarding lane position, participants with mild-to-severe TBI swerved more often on straight and curved paths (Lew et al., 2005; Liu et al., 1999; Schmidt et al., 2016). Additionally, persons with mild-to-severe TBIs exceeded the speed limit more than age and gender matched controls (Lew et al., 2005). Though not observed in mild cases, moderate-to-severe TBIs appear to produce inconsistency in speed and acceleration (Lew et al., 2005). In addition, persons with mild to severe TBI conducted less safety behaviors such as signaling quickly and checking mirrors. Thus, across severity and recovery stage, simulators capture differences between persons with and without TBI possibly explained by slower and less efficient thinking.

Cognition after TBI

Theory-driven cognitive domains.

Possibly explaining unsafe driving, cognitive difficulties following TBI are common and span several domains. There are several notable theoretical frameworks which help to describe these cognitive difficulties: information processing models from Atkinson and Shiffrin (1968) and current theories of working memory (Baddeley & Hitch, 1974) and executive function (Botvinick, Braver, Barch, Carter, & Cohen, 2000; Miyake et al., 2001).

In the Atkinson and Shiffrin (1968) model, human cognition is processed through several components including short-term and long-term memory under the control of the central executive (Baddeley & Hitch, 1974), consisting of specific executive functions (Miyake et al., 2001). In relation to driving, the first cognitive step is to perceive environmental stimuli and selectively transfer this information into temporary storage known as short-term memory, (i.e., what color is the traffic light). Information considered worthy for future reference (done explicitly or implicitly) then moves into long-term memory, a process also known as learning or encoding. This involves indefinite storage of learned symbols, schemas, and rules as well as experiences. Typically, storing information is not enough to make behavioral decisions but will also require manipulation and transformation of information by the central executive.

The central executive then manipulates and transforms short- and long-term memory to achieve cognitive-behavioral goals, such as driving safely, using basic executive functions: inhibition of irrelevant information or responses, shifting mental sets (switching rules and tasks), updating memory, and accessing long-term memory. For example, with the goal to drive safely through a traffic light, the central executive helps us drive safely by inhibiting distractions like billboards and music, switching between keeping headway distance and checking light color, updating active memory by removal or addition (removing information on other lane signals, adding information on your current light), and accessing long-term memory (this light does not work after 10:00pm). These functions then build higher-order factors of the central executive such as reasoning, problem-solving, and planning (Collins & Koechlin, 2012; Diamond, 2013) which help decide and implement complex driving behaviors such as trip navigation and defensive driving (Car & Frank, 1994).

As a theoretical consideration, executive functions do not implement on their own but through conflict monitoring from the central executive (Botvinick et al., 2000). Specifically, as tasks become difficult they necessitate greater information processing with inferring mental sets and modalities. For example, when driving safely, we input visual data for lane maintenance and speed control that contend for the same processor (central executive); however, because of dissimilar mental sets, the choice to slow down may interfere with moving towards the lane center. Instead, conflict monitoring from the central executive draws higher-order control (task switching, problem solving, planning) to generate motor behavior that allows us to slow down (hit brake) while also correct lane position (move wheel left). Alternatively, when merging into freeway traffic we may encode visual stimuli from left lane checks and auditory stimuli from approaching cars to avoid collision. Not only does this double the information in active memory but mixed sensory modalities muddle information. Stimuli overload and high complexity then forces the central executive to call upon unique mechanisms for cognitive control. These executive functions provide coherent goal-directed behavior by helping us proficiently shift between varied mental sets (set-switching) and minimalize irrelevant material (inhibition and updating).

Lastly, our ability to store and control competing information depends on how well we attend and process such information quickly. Good concentration involves doing so for long amounts of time (sustained attention), being able to focus on multiple stimuli at once or alternate your attention (divided attention) and focusing on stimuli relevant to current goals (selective attention). Processing speed involves the time to attend, store, and transform information to make proper decisions; typically, faster speeds are preferred to the extent that accuracy does not degrade.

Impact of TBI on objective cognition.

As expected from disturbed brain function, persons with TBI show cognitive disruptions months to years after injury (Schretlen & Shapiro, 2003), involving problems with memory, executive function, attention, and processing speed.

Most commonly, persons with moderate-to-severe TBI report trouble remembering (Arcia & Gualtieri, 1993; Oddy, Coughlan, Tyerman, & Jenkins, 1985). This involves greater difficulty remembering verbal (Brooks, 1974, 1975; Skandsen et al., 2010) and visual information short term (Skelton, Bukach, Laurance, Thomas, & Jacobs, 2000; Tabaddor, Mattis, & Zazula, 1984) but mostly involves problems recalling events and objects from long-term memory (Reid & Kelly, 1993). Specifically, individuals with TBI have difficulties in long-term memory in terms of acquisition, consolidation, and later retrieval (DeLuca, Schultheis, Madigan, Christodoulou, & Averill, 2000; Haut, Petros, & Frank, 1990; Haut, Petros, & Frank, 1991; Vanderploeg, Crowell, & Curtiss, 2001). To a lesser degree, similar findings are found for mild cases: Compared to healthy controls, individuals with mild TBI show worse performance on measures of short-term memory (*d*s range from .13 to .31) but even worse performance on measures of long-term memory (*d*s range from 60 to .71). However, memory problems can last 10 (Zec et al., 2001) or 30 years (Himanen et al., 2006) after moderate-to-severe TBI while only weeks after mild cases (Macciocchi, Barth, Alves, Rimel, & Jane, 1996). Memory problems involving trouble acquiring information for momentary use and long-term storage could explain the large deficit in learning shown after TBI (Shum, Harris, & O'Gorman, 2000).

In addition to memory, injury also harms the central executive and conflict monitoring – impeding goal-directed behavior. Regarding basic functions, most common impairments in moderate-to-severe TBI are deficits in updating (Foley, Cantagallo, Della Sala, & Logie, 2010) and set-shifting (Cockburn, 1995; Summers, 2006). Deficits in inhibition have also been reported (McDowell et al., 1997; Summers, 2006), but results are largely inconsistent (Rieger & Gauggel, 2002; Simpson & Schmitter-Edgecombe, 2000). On the other hand, participants with mild TBI exhibit problems inhibiting and set-shifting shortly after injury while findings are mixed for updating. Specifically, visuospatial updating appears similar for mild TBI (mixed mechanisms) compared to controls (Perlstein et al., 2004) but sub-normal in athletes with a history of concussion (Sicard, Moore, & Ellemberg, 2018). Accessing is also worse for persons with moderate-to-severe TBI compared to healthy controls (Henry & Crawford, 2004) involving poorer fluency in semantic and phonemic information. Persons with mild TBI are shown problems in accessing mainly involving fluency in non-verbal information (Mathias, Beall, & Bigler, 2004). On higher-order factors, some with moderate-to-severe TBI show impaired reasoning (Foley et al., 2010; Kersel, Marsh, Havill, & Sleigh, 2001) but most have intact planning (Cockburn, 1995). Most with mild TBI, however, do not show problems with these higher-order executive functions (Mathias & Wheaton, 2007).

To store and manipulate information, one must first be attentive; unfortunately, TBI weakens one's ability to maintain, divide, and focus awareness on stimuli needed for goal behavior. Most commonly studied, persons with mild (Chan, 2005) and moderate-to-severe TBI (Loken, Thornton, Otto, & Long, 1995; Stuss et al., 1989; Whyte, Fleming, Polansky, Cavallucci, & Coslett, 1998) are less able to sustain attention compared to non-injured peers. However, greater difficulty is seen for divided attention. Specifically, many persons with moderate-to-severe TBI have clinically-impaired divided attention (Povlishock and Katz, 2005; Hagmann et al., 2008; Robert & Schmitter-Edgecombe, 2017) while most persons with mild TBI show below-normal performance (Papoutsis, Stargatt, & Catroppa, 2014). Lastly, another common difficulty after mild and moderate-to-severe TBI is selective attention, mostly seen as an inability to avoid distraction (Bate, Mathias, & Crawford, 2001; Schmitter-Edgecombe & Kibby, 1998; Ziino & Ponsford, 2006; Zoccolotti et al., 2000). Thus, attention appears more difficult for complex (divided attention, selective attention) than simple processes (sustained attention). Findings align with the idea that attentional difficulty stems from a disrupted central executive, a control system needed for complex processes (i.e., attentional control). For example, deprived updating accounts for inability to divide attention (Serino et al., 2006) and disinhibition accounts for inability to selectively attend (Ries & Marks, 2005).

Enduring impediments are also shown in processing speed following mild and moderate-to-severe TBI. Second only to updating, impairment in processing speed are found in 46%-69% of persons with mild to severe TBI (Kersel et al., 2001; Serino et al., 2006). This results in greater elapsed time to make a series of accurate responses (Whyte et al., 1998), longer average reaction times to make an accurate response, and more variability in response times (Zahn & Mirsky, 1999). Slower processing is further exacerbated by greater task difficulty (Mathias et al., 2004) and distraction (Whyte et al., 1998). Similar to other debates in the literature, many have questioned if slower processing accounts for problems in other domains such as memory, central executive, or attention. While some research shows that slower processing can account for worse performance on central executive measures (Veltman, Brouwer, van Zomeren, & van Wolffelaar, 1996), others show that, while related, there are unique deficits in the central executive after controlling for processing speed (Serino et al., 2006). While influential, slow processing speed does not account for all problems after TBI.

Lastly, while not an issue for milder cases (Erez, Rothschild, Katz, Tuchner, & Hartman-Maeir, 2009), impaired self-awareness or anosognosia commonly occurs after moderate-to-severe TBIs. During the acute injury phase (<6 months after injury or initial rehabilitation), most individuals exhibit overconfidence to a degree greater than healthy controls (Allen & Ruff, 1990). More specifically, 76% to 97% of survivors show anosognosia acutely after injury (Sherer, Bergloff, Levin, High, Oden, & Nick, 1998a). This includes better ratings of cognitive, behavioral, and emotional skills than what families or clinicians observe (Sherer, Boake, Levin, Silver, Ringholz, & High, 1998b). One month after injury, 10% exhibit significant impairment in self-awareness defined as one standard error below significant other's ratings. Between skillsets, 18% of individuals report fewer psychosocial and 24% reported fewer physical issues than significant others (Pagulayan, Temkin, Machamer, & Dikmen, 2007). Even so, people more accurately rate sensory loss or physical impairment during this period than psychosocial issues (Sherer et al., 1998b). They also report more realistically when asked about specific behaviors or feelings rather than global abilities (Sherer et al., 1998). Lastly, Abreu, Seale, Scheibel, Huddleston, Zhang, and Ottenbacher (2001) found that participants with TBI can rate other's tasks performance normally but not their own. This points towards impaired metacognition, a disruption in subjective cognition, rather than problematic judgement.

Longitudinally, impaired self-awareness can persist over a year postinjury although it improves considerably (McKinlay & Brooks, 1984). For instance, Hart et al. (2009) found that while individuals with moderate-to-severe TBI reported better behavioral and emotional skills than their significant others at one year; but they similarly rated motor and sensory abilities. Moreover, self-ratings positively correlated with reports from significant others after twelve months that was not true in the acute phase. Godfrey, Partridge, Knight, and Bishara (1993) also found similar functional ratings between survivors and significant others one year after injury. In comparison to acute rates, Pagulayan et al. (2007) found that 3% of individuals with moderate-to-severe TBI showed reduced self-awareness one year later. This involved 18% and 11% anosognosia for psychosocial issues and physical issues, respectively. Despite this low prevalence, individuals report better skills than experienced rehabilitation staff seven years later (Trudel, Tryon, & Purdum, 1998).

As a note, impaired self-awareness might reflect performance in other cognitive domains. Theoretically, unawareness hinders conflict monitoring and, therefore, employment of executive functions for information manipulation and goal behavior. Bogod, Mateer, and MacDonald (2003) examined self-awareness among individuals with moderate-to-severe TBI nearly eight years postinjury. Overall, higher self-awareness related to better executive function (i.e., updating and inhibition) and general intelligence. Around a similar time since injury, Bivona et al. (2008) found that worse set-shifting related to impaired self-awareness but not problems in verbal fluency, selective attention, or memory. Moreover, Hart, Whyte, Kim, and Vaccaro (2005) described more discrepant self- and informant-rated executive function for those with poorer executive function (based on performance tasks) than higher executive function, although statistically insignificant. Nevertheless, many studies fail to implicate relations between impaired self-awareness and objective cognition in terms of intelligence (McGlynn & Schachter, 1989) and executive function (Bach & David, 2006; Lanham et al., 2000; Prigatano et al., 1998; Ranseen et al., 1990; Stuss & Levine, 2002). Thus, impaired self-awareness appears as a separate but impactful issue after moderate-to-severe TBI that can take years to recover.

Cognitive difficulties can be extensive after TBI and, while measured in the laboratory or clinic, they disrupt everyday living. For example cognitive skills predict long-term psychosocial adjustment (Hanks, Rapport, Millis, & Deshpande, 1999; S. R. Ross, Millis, & Rosenthal, 1997), disability (Neese et al., 2000; Novack, Bush, Meythaler, & Canupp, 2001), employment (Novack et al., 2001; Sherer, Novack, et al., 2002), productivity (Boake et al., 2001; Sherer, Sander, et al., 2002), and community reintegration (Novack et al., 2001). Problems with cognition also predict higher inattentive behavior (Kim et al., 2005), gait stability (Parker, Osternig, Lee, van Donkelaar, & Chou, 2005), and problems navigating complex environments (Cantin et al., 2007). Adding to this literature, the current review investigates the impact on a recently acquired, intricate human skill: the ability to drive.

Impact of TBI on subjective cognition.

Cognitive task performance is the golden standard to indexing mental abilities after pathology; however, subjective cognition shows important disruptions too. Subjective cognition involves the meta-cognitive monitoring of our own abilities to do various tasks such as remember, think quickly, and multitask. Apart of self-awareness, we achieve this perception either through online monitoring, rating our abilities while performing a task, or offline monitoring, rating our global abilities based on declarative knowledge of skill (Metcalfe & Schimamura, 1994).

Even with lingering anosognosia, persons with TBI report poorer cognition when offline monitoring (Hart et al., 2009). The most common cognitive complaint is trouble remembering, reported in 18 to 40% of persons with mild to severe TBI (Masson et al., 1996). In fact, adults with TBI are 29% more likely to develop subjective memory impairment even 38 years after injury (Gardner, Langa, & Yaffe, 2017). Adding to this forgetfulness, over 44% of people with mild TBI report slowed thinking and poor concentration within 24 hours of injury (de Boussard et al., 2005). Moreover, these symptoms are persistent, lasting longer than most objective difficulties: Over three months after mild TBI, 26% reported impaired memory, cognitive speed, and attention (de Boussard et al., 2005). In addition, though individuals with mild TBI were similar to uninjured peers on emotional and physical function 3 months after recovery, they had ongoing memory and concentration difficulties (Ponsford, Cameron, Fitzgerald, Grant, & Mikocka-Walus, 2011). Even 8 years later, there are higher cognitive failures reported in mild TBI than in healthy controls concerning lapses in memory and attention control (d = .75; Dean, O'Neill, & Sterr, 2012).

After moderate-to-severe TBI, subjective problems with memory and problem-solving are prevalent (34.1%); and survivors characterize cognitive problems as more concerning than managing stress and emotions (27.9%) or managing finances (Corrigan, Whiteneck, & Mellick, 2004). People incurring moderate to severe TBI also describe greater cognitive failures and executive dysfunction compared to healthy controls 2.5 years after injury (d = 1.40; Hart, Whyte, Kim, & Vaccaro, 2005). Moreover, individuals with moderate to severe TBI reported greater cognitive failures than healthy controls (d = .62) nearly 3 years after injury (Whyte, Grieb-Neff, Gantz, & Polansky, 2006).

More mixed findings appear for online metacognitive monitoring after TBI. In one of the first studies, Kennedy & Yorkstron (2000) conducted a judgment-of-learning task in persons with moderate TBI. In this task, participants reported their confidence to recall three-word lists – judged either immediately or after a while since studying. Overall, adults with TBI were just as accurate in their judgements as controls when making delayed predictions but were overconfident after immediate judgments. More recently, Chiou, Carlson, Arnett, Cosentino, & Hillary (2011) implemented metacognitive monitoring using standard neuropsychological tests. In this study, individuals with moderate-to-severe TBI and heathy controls completed an assessment of higher-order executive functions (Matrix Reasoning Subtest of the WAIS-III and Abstraction subtest from the Shipley's) and memory (HVLT-R). Researchers modified instruments so that participants reported how accurate they believed each answer to be (from completely certain to completely uncertain) for each trial. On objective cognition, participants with TBI performed worse on all tests compared to controls (*d*s range from 1.18 to 1.50). Regarding online monitoring, participants with and without TBI were alike in perceptions of accuracy during higher-order executive function tasks (60 versus 70% concordance) but perceptions were less accurate on memory tasks (20% concordance versus 50%).

O'Brien & Kenney (2016) further examined online meta-memory monitoring in TBI versus controls. For this task, participants learned certain cues (when to conduct action) and tasks (action to be completed) prior to completing a virtual reality week (simulated Monday through Friday). During each simulated day, software showed participants a series of pictures and then asked if they had a task to complete or not. Both groups performed equally remembered task cues but adults with TBI forgot what the actual task was more often than controls. Despite this, the group with TBI reported better self-rated performance than their actual performance while the reverse was true for controls: healthy adults rated themselves as doing worse than their actual performance. Thus, unawareness after TBI appears to reflect inaccuracies during immediate online monitoring of memory rather than executive function or delayed memory judgments.

Relevant to the current study, offline monitoring appears to show divergent validity between TBI and healthy controls. Furthermore, cognitive self-ratings appear most accurate when they evaluate complex decision-making and when provided some delay. This appears important in the context of driving as one must recently complete the task and provide delayed online ratings to provide reliable ratings. Because immediate on-road driving imposes danger, however, offline cognitive ratings may serve as a useful proxy for difficulties in car operation.

Subjective and objective cognition.

Much discussion regards the extent to which undesirable self-ratings of cognition reflect abated performance. Overall, cognitive self-ratings appear moderately related to certain cognitive performance domains albeit modestly. In mild TBI, researchers found connections between self-reported cognitive failures and worse processing speed and updating – though insignificantly related to other higher-order functions such as set-shifting and reasoning. Moreover, Schiehser et al., 2011 found that greater self-reported problems in executive function related to problems in processing speed, updating (Digit Span), and set-shifting (Trail Making Task Part B) but not memory (Wechsler Memory Scale-III: Visual Reproduction and Recognition; California Verbal Learning Task-II: Long Delay Free Recall and Recognition task).

Among moderate and/or severe TBI, self-reported cognitive problems reflected slower cognitive speed but also disrupted memory and executive function. Johansson and colleagues (2009) found that patients reporting mental fatigue were slower on several processing speed measures (Trail Making Task Part A, Digit Symbol Coding, and

Reading Speed). Patients with mental fatigue also scored worse on set-shifting (Trail Making Task Part B) and updating tasks (Digit Span and Spatial Span). Moreover, Chamelian and Feinstein (2006) found that participants with cognitive complaints (“subjective memory complaints”) scored worse on measures of short- and long-term memory (California Verbal Learning Task: Recognition, BVMT-immediate and Delayed Total Recall); they also did worse on measures of updating (Wechsler Adult Intelligence Scale-III) and divided attention (Paced Serial Addition Task 2.0). Lastly, Robertson et al. (1996) found that self-reported attentional failures related to worse sustained attention (Sustained Attention to Response Task). Overall, subjective cognitive complaints after TBI somewhat reflect problems in higher order thinking and slower processing speed.

Depression and cognition.

Negative affectivity after TBI can engender substandard cognitive performance and self-ratings (Seidenberg, Taylor, & Haitiner, 1994). Throughout cognitive literature, higher depression relates to worse cognitive task performance (McDermott & Ebmeier, 2009; McClintock, Husain, Greer, & Cullum, 2010) and higher cognitive complaints (Balash, Mordechovich, Shabtai, Giladi, Gurevich, & Korcyzn, 2012; Julian, Merluzzi, & Mohr, 2007). This is important as 53.1% of individuals with mild to severe TBI meet Diagnostic Statistical Manual criteria of major depressive disorder during the first year of recovery (Bombardier et al., 2010) that drops to 27.0% around 3 years later (Seel et al., 2003). Indeed, individuals with depression after mild to moderate TBI exhibit worse cognitive speed, verbal memory, and executive function (e.g. updating and set-shifting) indexed from objective tasks compared to non-depressed survivors (Rapoport, McCullagh, Shammi, & Feinstein, 2005). Farrin, Hull, Unwin, Wykes, & Davd (2003) described similar results and noted as a potential mechanism for worse performance in depression. Overall, adults with TBI and depression committed more errors on a sustained attention task than those without depression. Post-hoc testing then revealed that participants with depression slowed their performance after each subsequent error. Authors attributed this phenomenon to negativity biases in depression: Hypersensitivity to negative sensations caused rumination and poor attentional shifting from cognitive failures that cumulatively slowed performance. This aligns with findings in older adults that depression provokes greater error awareness (Buckley, Laming, Chen. Crole, & Hester, 2016).

Depressed mood also contributed to feelings of poor cognition. Greater depressive symptoms in veterans with mild TBI positively link to difficulties in memory, attention, and slowed thinking (Spencer, Drag, Walker, & Bieliauskas, 2010). Six months after mild to moderate TBI, diagnosis of major depression disorder corresponded to reports of forgetfulness, poor memory, poor concentration, and slowed thinking (Chamelian & Feinstein, 2006). Attending to negative sensations may then help one catastrophize cognitive errors though such worries misalign with actual abilities. In fact, depressive symptomology appears to weaken relations between subjective ratings and cognitive task performance: Boake, Freeland, Ringholz, Nance, & Edwards (2009) found reduced correlations between ratings of forgetfulness and scores on memory tasks (though still significant) in persons with depression or negative response bias compared to persons without depressive feelings. Similarly, after controlling for major depressive disorder, Chamelian & Feinstein (2006) found that many relationships between subjective cognition and task performance dissolved. Consequently, it is important to control for depressed mood when examining aspects of subjective cognition and correlates to actual ability.

Cognition and Driving after TBI

Driving is a complex behavior calling upon various cognitive abilities to navigate safely. As an example, younger adults with weaker updating exhibit worse lane maintenance (Mäntylä, Karlsson, & Marklund, 2009). Whereas, poor executive control (inhibition and set-shifting), weakened memory, and slowed reaction times elevate crash risk in older adults (Anstey, Wood, Lord, & Walker, 2005). Objective cognition may then account for differences in driving outcomes following TBI compared to peers. To elucidate such mechanisms, we conducted a narrative review on cognitive correlates of driving ability following TBI. The specific purpose of this review was to summarize literature examining how objective and subjective cognitive ability link to driving competency among individuals with mild and moderate-to-severe TBI.

Objective cognition and return to drive.

Some articles examined cognitive predictors of return to drive measured by continuous driving exposure or categorizing drivers from non-drivers. Looking specifically at moderate-to-severe TBI (n = 184), Labbe et al. (2014) found that greater cognitive function indexed by better short-term memory, updating, processing speed, and set-shifting ability was associated with greater amount of time driven after injury. Studies on mild TBI show similar findings, with quicker hazard reaction time and processing speed associated with shorter delays in return to driving (Preece et al., 2012).

Cognition can also differentiate between people who resume driving from persons unable to do so. Persons with mild injuries who return to driving show better cognitive function indexed by hazard reaction time, executive functioning, planning, decision making, and attention (Baker et al., 2015).

Objective cognition and driving.

Many studies examine cognitive predictors of driving ability, including fitness to drive (dichotomous outcome of pass or fail) and indexed performance (continuous outcome). Qualifying driving fitness involves on-road evaluation with a professional who decides competency. Though not definitive, cognitive testing may aid such decisions. Looking from mild to severe injuries, Hawley et al. (2001) found that categorizing persons by general memory or concentration problems (yes or no) did not distinguish individuals who returned to driving from those not returning after TBI. Continuous performance measures, however, are more fruitful. In the earliest study, Coleman et al. (2001) administered cognitive tests to 71 persons with TBI while obtaining their driving status. Compared to post-injury drivers, non-drivers showed lower cognitive skills involving slower processing speed, reasoning, and set-shifting. There was also a trend for better updating in drivers compared to non-drivers. Other test batteries successfully distinguishing fit from unfit drivers: Radford et al. (2004) found that better performance on the Cognitive-Behavioral Driving Index correctly classified 87% of individuals as fit or unfit to drive. Specifically, better processing speed, reasoning, inhibitory control, and updating/sustained attention related to greater chances of passing on-road driving evaluation. Bouillon et al. (2006) added to these findings, showing that an alternative battery discriminated fit from non-fit drivers. Along with better vision, Bouillon et al. (2006) found that drivers passing on-road assessment had better cognitive skills involving quicker reaction time, processing speed, and set-shifting compared to persons failing the test. No significant differences appeared on visual reasoning, however.

Two recent studies illustrate the importance of cognition for competent driving. McKay et al. (2016) examined 99 persons with mild to severe TBI who underwent on-road assessment and cognitive testing. Instructors rated participants on appropriate/inappropriate driving behavior while navigating intersections, changing lanes, merging, and parking through low and high traffic conditions; results informed decisions on fitness (conditional or unconditional pass/fail). Results showed that persons with lower cognitive skills were less competent to drive, involving problems in short-term memory, visual-spatial reasoning, verbal reasoning, set-shifting, and updating. Gooden et al. (2017) tested similar skills but found that individuals with moderate-to-severe TBI with difficulties in visuospatial reasoning were less likely to achieve driving fitness but no stark differences on processing speed, set-shifting, or inhibitory control. Earlier and concurrent work supports confluence between disrupted cognitive and driving ability.

On-road ratings, self-report scales, and driving simulators have allowed researchers to not only test the effect of cognition on suitability to drive, measured dichotomously, but also the ability to account for subtle variation in risky driving, measured continuously. In the earliest found study, Mosberg et al. (2000) found a marginal trend towards poorer executive functioning and more frequent crashes after injury. Cyr et al. (2009) examined cognitive function of persons with moderate-to-severe TBI (*n* = 17) and the number of crashes incurred during simulated driving. Individuals who had trouble quickly dividing attention had a greater number of simulated crashes; participants with poorer set-shifting tended to incur more simulated crashes as well. Recently, Schmidt et al. (2017) found that this poorer cognition also related to greater crashes after mild TBI: Difficulties in short-term memory or visual-reconstruction related to greater simulated crashes after concussion.

Though cognition can detect drivers fit and unfit to drive, a larger question is if cognitive ability can account for variations in overall driving ability. In the earliest study, Galski, Bruno and Ehle (1992) recruited 35 people with cerebral damage (22 persons with TBI, 13 with CVDs) referred for formal driving evaluation. Participants completed an extensive battery of cognitive measures testing attention and scanning ability, processing speed, visual-spatial problem solving, and reasoning. After testing, participants completed on-road driving assessment from a certified instructor. Cognitive measures were indeed predictive, accounting for 64% of the variance in on-road driving performance as indexed by the driving evaluators. Specifically, slower processing, decreased visuospatial problem-solving and diminished reasoning were associated with substandard driving.

Adding to these findings, Novack et al. (2006) examined relations between cognition and continuously rated fitness in various abilities. For this study, participants with TBI (72% severe, *n* = 60) underwent cognitive testing and on-road driving assessment. Besides making pass or fail decisions alone, a certified occupational therapist completed the Global Rating Scale while a research assistant in the back seat completed a lab-developed Driving Assessment Scale (DAS) to evaluate driving aptitude. The therapist used the DAS in practice to rate participant's difficulty in 25 different driving behaviors important for safe driving. The Global Rating Scale gives judgements on fitness to drive (0 = Should not drive up to 3 = Able to drive in any condition). Results found that lower cognitive skills associated with variations in driver ability: worse set-shifting (Trails Making Task-B) associated with more failure ratings on the Global Rating Scale but not the DAS. Moreover, divided attention, but not other measures of visual attention, associated with lower driving ability measured by the Global Rating Scale as well as the DAS. Thus, better cognition, indexed by processing speed and divided attention, were predictive of better driving aptitude after TBI.

More recently, Goodin et al. (2017) examined on-road driving ratings and cognitive tests in adults with moderate-to-severe TBI (n = 37). In addition to processing speed, set-shifting, and planning ability related to better driving performance. However, there was no association between on-road evaluations with inhibition or visuospatial reasoning.

Although the standard, research on cognition and on-road driving might not be fully generalizable to the TBI population. Specifically, people given the opportunity for an on-road evaluation are a select group with permission to attempt vehicle operation. In Alabama, for example, participants must receive a physician's prescription for the test in efforts to keep both driver and evaluator safe. For this reason, such individuals already demonstrate better recovery (often based on cognitive testing) than other individuals (e.g., Korteling & Kaptein, 1996). These studies, therefore, might not fully explain why some survivors with greater injury or worse recuperation exhibit poorer driving aptitude.

To fill this gap, driving behavior scales and simulation provide worthwhile and safe avenues to capture wide ranges of cognition and driving behavior.

Alongside crash counts and globally rated driving ability, several studies examined how cognition relates to more specific, risky driving behaviors. Preece and colleagues (2012) administered an ecological measure, Driving Behavior Questionnaire (DBQ), to 42 individuals with mild TBI; participants also underwent cognitive assessment on hazard reaction time, processing speed, and intelligence. The DBQ is an inventory of self-reported driving errors, failures to carry out driving-related goals with possible dangerous outcomes, and violations, deliberate actions against safe driving standards. Results found that slower hazard reaction time associated with more frequent driving errors after injury though not related to violations. Though other cognitive measures were not associated with driving behavior, hazard reaction time was dependent on one's processing speed and intelligence, showing possible indirect effects.

Simulators are also useful for collecting information about driving ability on specific behaviors. In the first study testing simulated driving skills after TBI, Galski, Bruno and Ehle (1992) also had adults with cerebral TBI and CV complete simulated driving in addition to comprehensive cognitive testing and on-road evaluation. Cognitive performance loaded into indexes of simulated driving performance: Poorer short-term memory, slower processing speed, and restricted visuospatial problem solving corresponded to more signaling and steering errors during the simulated drives. In addition, worse short-term memory and processing speed linked to more steering and braking errors. Alongside cognitive scores, the simulator scores (% signaling errors, %

threat recognition and valid steering) accounted for 70% of the variance in on-road driving – showing ecological validity.

Later Schmidt et al. (2017) examined simulated driving ability in persons with mild TBI (*n* = 14) after administering an extensive battery of cognitive tasks. Results found that problems with set-shifting and overall executive function related to more driving violations (tickets) while problems with memory related to poor lane maintenance: Problems with verbal memory related to more lane excursions and road edge excursions, problems visual short-term memory related to more centerline crossing. Processing speed was also important with slower speed related to more roadway excursions.

Subjective cognition and driving.

Aside from performance, cognitive self-reports may help predict driving performance in TBI. Ideally, understanding cognitive problems allows one to implement compensatory strategies and regulate behaviors accordingly; this is known as metacognitive control (Neslon & Narens, 1990). However, there is an apparent disconnect for many untrained or cognitively compromised individuals as metacognitive control relies on learned strategies and complex implementation from conflict monitoring and executive functions (Ben-Yishay & Diller, 1993). Because of disruptions in long-term memory and executive function, metacognitive judgements in TBI produces inadequate behavioral adjustments (Ganesalingam, Sanson, Anderson, & Yeates, 2006; Sesma, Slomine, Ding, & McCarthy, 2008). Indeed, many individuals will require training on meta-cognitive strategies (i.e., planning, organization, self-regulation) to improve cognitive and functional activities after injury (Kennedy et al., 2008; Ownsworth, Fleming, Desbois, Strong, & Kuipers, 2006). Metacognitively perceived impairment from offline monitoring might therefore correspond to ongoing difficulties daily activities like driving.

Research supports that without strategy training, worse ratings of cognition link to problematic driving and incident collisions. For example, Kass, Beede, and Vodanovich (2010) showed that perceived cognitive failures links to greater deviation in lane position, slower reaction times, and attentional lapses on the roadway. Cognitive failures also related to more driving errors in licensed professionals (Allahyari et al., 2015) and collisions in military recruits (Larson & Adlerton, 1997). Moreover, metacognitions of poor inhibition and attention control relate to driving errors and violations (Wickens, Toplak, & Wiesenthal, 2008). Among typical adolescents, Pope, Ross and Stavrinos (2016) found that self-reported difficulties in executive function, mainly planning and organization, were associated with higher odds of an MVC, whereas failures in inhibition were associated with receiving a ticket, and multiple domains of executive function associated with getting pulled over by the police. Self-reported problems with executive function also predict distracted driving across the lifespan (Pope et al., 2016), a risk factor for MVCs in both healthy and TBI populations.

The Current Research Goal

To date, there has been few studies examining subjective cognition and driving after TBI. Concerning return to drive, Caplan et al. (2017) found that better ratings of cognitive function related to greater independent driving after mild to severe TBI. Leon-Carrion et al. (2009) found that individuals with severe TBI who returned to driving post-injury had better ratings of cognitive function compared to persons no longer driving. Recently, Rike et al. (2010) found that lower self-ratings of executive function related to greater pre-morbid violations, mistakes, and inattention on the roadway in persons with TBI. Researchers did not investigate post-injury driving behaviors though one can expect that subjective cognition was still relevant. To fill critical gaps in this content area, the goal of the current study is to examine how subjective cognition, captured comprehensively through mental fog, predicts driving performance after TBI over and above scores on objective cognitive tasks.

CHAPTER 2

SPECIFIC AIMS

AIM 1: To compare severity of mental fog in mild and moderate-to-severe TBI to healthy controls while controlling for depressed mood.

Preliminary studies suggest significant mental fog in persons with TBI (Corrigan et al., 2004; de Boussard et al., 2005) but validation of this symptom cluster requires comparison to healthy controls. If persons with and without TBI are comparable on mental fog, then classification as an injury-related symptom is unclear. Secondly, testing between persons with mild and moderate-to-severe TBI is another step for validation to determine if this symptom corresponds to injury severity. If mental fog presents similarly across injured and non-injured groups, as well as between severities, the ability to explain group differences in driving would appear weak. Thus, there is a need to examine group differences in mental fog prior to evaluating relations to cognitive function and driving within TBI.

To validate mental fog as an injury-specific symptom, this study analyzed data from two studies using a novel and detailed cognitive screener, the Mental Clutter Scale (MCS). The MCS subjectively captured feelings of "mental fog" involving difficulties with memory recall, sensory overload, blurred mental activity, ability to think clearly, process information, and follow conversation (Katz et al., 2004). Additionally, the MCS is a reliable and valid assessment for clinical samples (Leavitt & Katz, 2011), strongly related to problems in everyday activities of daily living (Bell, Shelley-Tremblay, &

Christensen, 2015). Thus, the MCS appears useful for a clinical sample such as TBI to predict driving behavior, one of the most common activities of daily living.

Hypothesis 1a. Because persons with TBI report significant levels of "fogginess" in addition to objective performance decrements (de Boussard et al., 2005), it is predicted that mental fog will be greater in persons with TBI compared to healthy controls on the Mental Clutter Scale.

Hypothesis 1b. Additionally, because objective and subjective cognitive difficulty increases with injury severity (Goldstein, Levin, Goldman, Clark, & Altonen, 2001; F. Masson et al., 1996), we predicted that self-reported mental fog will be greater in persons with moderate-to-severe TBI compared to mild cases. Alternatively, there is a possibility that poor self-awareness after moderate-to-severe TBI could lower self-reported fog compared to mild cases (Hart, Seignourel, & Sherer, 2009). However, survivors reported mental fog within months to years after injury in which awareness of problems improves dramatically (Hart et al., 2009). Further, the impact on mental fog is not known, making this study among the first to compare mental fog in persons with moderate-to-severe TBI, and to compare levels of mild cases.

Because negative affectivity can inflate subjective cognitive complaints (Chamelian & Feinstein, 2006), sensitivity analysis examined these hypotheses while controlling for depressed mood.

AIM 2: To examine if mental fog reflects problems in objective cognitive performance over and above depressed mood.

In previous research, subjective cognitive complaints after TBI correspond predominately to slower processing speed but also greater problems in memory and executive function. Thus, there is a need to evaluate how mental fog within two severity classifications relates to performance-based cognition. Using the Cogstate Brief Battery® and the Useful Field of View (UFOV®), we hypothesized that greater mental fog relates to greater problems in objective cognition though the specific domains may differ by severity.

Hypothesis 1a. Aligning our hypotheses with prior findings (Schiehser et al., 2011), we predicted with persons with mild TBI who report greater mental fog will show slower processing speed (Cogstate® Detection and Identification tasks; UFOV®1 – Speed of Processing) and worse updating (Cogstate® One-back task). We explored relations with memory (Cogstate® Learning task), divided attention (UFOV®2) and selective attention (UFOV®3 and 4).

Hypothesis 1b. From prior literature (Chamelian & Feinstain, 2006; Johansson et al., 2009; Robertson et al., 1996), we hypothesized that greater mental fog in moderate-to-severe TBI will correspond to slower processing speed (Cogstate® Identification and Detection, UFOV®1 – Speed of Processing) as well as worse memory (Cogstate® Learning Task), updating (Cogstate® One-Back Task), and divided attention/shifting (UFOV®2). Another reason why mental fog may relate to the Cogstate® Detection and Identification tasks is that it also captures sustained attention (see Betts, Mckay, Maruff, & Anderson, 2006). Though not shown directly in the literature, greater mental fog may relate to problems in selective attention UFOV® 3 and 4 due to demands on higher-order executive function (i.e., selective attention) – harmed by moderate-to-severe TBI (e.g., Bate, Mathias, & Crawford, 2001).

Because negativity bias can weaken relations between subjective and objective indices of cognition (Boake et al., 2009; Chamelian & Feinstein, 2006), sensitivity analysis tested the following hypotheses while controlling for depressed mood.

AIM 3: To examine if mental fog relates to driving outcomes after mild and moderate-to-severe TBI involving simulated driving abilities and MVCs over and above objective cognition.

Persons with TBI are potentially at greater risk for roadway injuries (Bivona et al., 2012), related to obstructed driving ability in both mild (Schmidt et al., 2016) and moderate-to-severe TBI (Schanke et al., 2008). Thus, studies are needed to better understand reasons for impeded driving following TBI. To date, several have examined the role of objective performance on driving outcomes and behavior after TBI as they are integral to driving (Mäntylä et al., 2009) and disrupted after mild and moderate-to-severe TBI. Many studies support that lower cognitive ability related to poorer driving ability both on the road and in simulators (Duquette et al., 2010; Novack et al., 2006). An emerging line of research shows that self-report measures may additionally predict poor driving after TBI (Pope, Bell, & Stavrinos, 2017; Pope, Ross, & Stavrinos, 2016; Rike et al., 2014). The current study will expand this research by examining how self-reported problems with mental fog, one of the most common reported difficulties in cognition, can predict driving outcomes and simulated driving ability in a cross-sectional evaluation of individuals with mild and moderate-to-severe TBI.

To test this hypothesis, we conducted secondary data analyses from two studies looking at simulated driving in persons with mild and moderate-to-severe TBI. The first study recruited 16 adolescents and young adults seen within 2 weeks of a mild TBI. These participants completed a practice and realistic simulated drives. For the current project, we looked at simulated driving that occurred on a 4-lane highway with ambient traffic. The second study enrolled 15 adults who received a moderate-to-severe TBI within the last two years. The current project looked at two simulated drives on a four-lane highway without and with ambient traffic, respectively; neither contained auditory distraction. This allowed us to test driving ability from similar environments in persons with mild and moderate-to-severe TBI. The simulator recorded their speed control and lane maintenance in terms of average and variability in speed and lane position. The number of simulated on-road MVCs were also recorded. After the simulation, participants completed the Brain Injury Self-Awareness Questionnaire (BIDSAM, Gooden et al., 2016) to measure self-reported difficulty in simulated driving.

Hypothesis 1. Because self-reported cognitive difficulty can tap into key cognitive domains related to driving (Chamelian & Feinstain, 2006; Johansson et al., 2009; Schiehser et al., 2011) and predict crashes and driving errors (Pope et al., 2016; Pope et al., 2017), we hypothesized that greater mental fog (Mental Clutter Scale total score) will relate to poorer speed control (higher average speed, greater variability in speed), poorer lane maintenance (higher average lane position, greater variability in lane position), and greater risk of a MVC. We also predicted that it would relate to greater self-reported difficulties in driving encompassing ratings of speed control, lane maintenance, and safety behavior (BIDSAM). We expected mental fog to relate to such outcomes over and above objective cognition like the work by Pope et al. (2016) on self-reported problems in executive function.

Because objective cognition performance impacts driving (e.g., Galski, Bruno, & Ehle, 1992; Novack et al., 2006; Schmidt et al., 2017), hypothesis testing controlled for objective task performance to better understand the unique role of mental fog. Additionally, analyses further controlled for the effects of months since licensure, as driving experience highly ties to driving skills (Kass, Cole, & Stanny, 2007; Lajunen & Summala, 1995). As mentioned, individuals with training can compensate for perceived difficulties (Kennedy et al., 2008; Ownsworth et al., 2006); therefore, longer driving experience may diminish the impact of mental fog due to compensatory strategies.

CHAPTER 3

METHODS

Participants

Mild TBI study.

Thirty-two adolescents and young adults (ages ranged from 16 to 25 years) including 16 with a mild TBI with 16 controls matched on age, gender, and driving experience (months since licensure) were recruited. Persons with mild TBI were recruited at local concussion clinics within two weeks of injury, after they received a physician-diagnosed mild TBI. Healthy controls (who had no prior history of self-reported concussion) were recruited via community advertisements.

Participants were a part of a larger study examining return to drive after mild TBI. Once referred or interested, participants underwent a telephone screening to ensure eligibility to participate. Inclusion criteria included that participants must have a valid driver's license and have driven in the past 12 months. Secondly, for the TBI group, participants met criteria of mild TBI by reporting substantial symptoms on the Post-Concussive Symptom Scale (individuals scoring 13 and greater were eligible; Chen, Johnston, Collie, McCrory, & Ptito, 2007; Lovell et al., 2006) and experienced one of four symptoms: (1) loss of consciousness ≤ 30 minutes (2) loss of balance or motor coordination (3) disorientation or confusion (4) loss of memory and (5) dizziness, headaches, nausea, fatigue, vomiting, etc. (Kay et al., 1993). For the control group, participants matched a participant with mild TBI on their age in years, gender, and months since licensure. Exclusion criteria for all participants involved if they had a physical disability that prohibited full participation in the driving simulator. Additionally, participants with mild TBI or controls were excluded if they suffered a head injury from a MVC, suffered a head injury that was intentional (e.g., assault or self-harm), or had a head injury that required hospital admission. Upon further review, one person in the mild TBI group did not meet the proper cutoff for mild TBI on the Post-Concussive Symptom Scale (participant score was 4 not ≥ 13) and was excluded from further analyses.

Moderate-to-severe TBI study.

The second study collected 15 participants with a diagnosed moderate-to-severe TBI, ages 21 to 50 years, referred from the UAB Traumatic Brain Injury Model Systems. Participants were a part of a larger study looking at fitness to drive and simulated driving after TBI. The moderate-to-severe TBI group consisted of persons varying in their driving status (per clinician report): 8 persons who were active drivers and 8 who were not driving at time of assessment. Participants in the active driver group were released to drive by their doctor, drove 3 or more times a week, were not involved in an at-fault MVC is the last 24 months, and did not receive a moving traffic violation in the last 24 months. For the no driving group, participants reported that would never be able to drive again (and clinicians agreed). Inclusion criteria for the TBI group included participants who had a moderate-to-severe TBI diagnosed by a physician in the last 24 months. Participants were excluded if they did not have a valid driver's license, did not drive pre-injury, and/or were unable to physically operate the simulator (e.g., comorbid motor disability).

Measures

Demographics.

From telephone screening, participants provided information on their age, gender, race, and ethnicity. They also provided information on when they received their driver's license; this was used to calculate months since licensure. Lastly, information was collected on their injury including date of the most recent head injury, number of previous TBIs or head injuries, activity involved in injury, and mechanism of injury. A list of current medications was also obtained at their appointment.

Driving history.

A driving history questionnaire obtained information on driver experience and record. For experience, participants provided information on when they obtained their permit and license. Participants then report the number of MVCs, times pulled over by police, and tickets in the last 3 years. For each event, they provided the date, if they were at-fault, and if they were engaged in secondary tasks when the incident occurred. We calculated time since licensure as an indicator of driver experience as a possible covariate in Aim 3. We compared groups descriptively on prior crashes and violations to inspect pre-morbid driving history.

Driving simulator.

Driving simulation was conducted in a high-fidelity simulator using a Realtime Technologies (RTI)® platform. This system involved participants sitting in a real cab of a 2016 Honda Pilot with the original interior. Outside of the car was a 180-degree projection of the simulated roadway environment in addition to a projection behind the car to be seen by rear-view mirror. In addition, side-view mirrors included LCD's displaying the backside of the roadway like a regular car. Inside, a computer displayed a digital speedometer and tachometer as well as fuel level and engine temperature. To improve the ecological-validity of the simulated drive, the cab was placed on a 1 degree of freedom motion base to mimic breaking and acceleration pitch cues, thus making the simulation feel more realistic compared to stationary simulation (Jorge, Tudon-Martinez, & Salinas, 2017). From each drive the simulator indexed speed control (*M* and *SD* miles per hour), lane maintenance (*M* and *SD* feet from center of lane) and collisions – all shown to be important for the TBI population (Classen et al., 2011; Lew et al., 2005; Liu et al., 1999; Schmidt et al., 2016; Sivak et al., 1981; Stokx and Gaillard, 1986).

Driving scenarios.

Mild TBI study.

Two drives were relevant for the current proposal. First, all participants completed a calibration drive in order familiarize them to operating the stimulator and reduce the impact of novelty on driving outcomes. The calibration scenario involved a 4-lane highway with no ambient traffic. Participants drove for nearly 5 minutes and were monitored by the experimenter to ensure correct operation and navigation. After the practice drive, participants completed a driving scenario on a 4-lane highway with ambient traffic. This scenario involved posted speed limits and curves.

Moderate-to-severe TBI study.

In this study, participants also completed a calibration drive. This involved driving on a road and left-hand making turns at a stop sign. This helped familiarize them to the driving simulator and reduce the impact of novelty on driving outcomes. In addition, the experimenter was blind to the fitness to drive decision from the doctor to minimize bias in how they assisted the participant with the simulation. The participants then completed two drives with posted speed limits involving freeway driving. The first involved no ambient traffic that captured basic car operation skills. Meanwhile, the second involved viewing billboards and keeping track of ambient traffic; both demands made this scenario more generalizable to everyday driving than assessing simple car operation alone.

Self-reported driving difficulties.

At the end of their appointments, all participants completed the Brain Injury Driving Self-Awareness Measure (BIDSAM, Gooden et al., 2016) to rate their driving difficulties during simulation. This instrument involved 28 items assessing overall performance (22 items) and difficulty and errors. For overall performance, participants rated 6 items on a 5-point scale (e.g., “very poor” to “excellent”). Examples include “How well do you think you performed on the driving assessment today?” and “How well were you able to maintain your concentration?" Next, participants reported on 22 items measuring how frequently difficulties and errors occurred during the simulated drives on a 3-point scale (e.g., "no", "occasionally", and "frequently"). Example items include "I had difficulties accelerating smoothly" and "I had difficulty merging into traffic." Items scores are summed to where higher values indicate greater driving difficulty. Showing adequate validity, Gooden et al. (2016) found that participants with TBI who failed a standard driving assessment reported higher driving difficulties scores when compared to participants with TBI who passed (d = .89) and non-TBI healthy drivers (d = 1.17). Showing construct validity, scores on the BIDSAM modestly correlate with the Driving Observation Scale (Gooden et al., 2016), a golden rating scale for driving instructors (r = .45, p < .05; Gooden et al., 2017). Regarding reliability, the BIDSAM total score shows high internal consistency in prior studies (α = .83; Gooden et al., 2017). We summed all items on the BIDSAM to create a self-reported driving difficulty score as done before (Gooden et al., 2017). Within our study, reliability was good to excellent in our samples (αs range from .80 to .91).

Mental fog.

Mental fog was measured by the Mental Clutter Scale (MCS; Leavitt & Katz, 2011). The MCS was developed to provide a detailed scale of mental fog over two dimensions: (1) problems with cognition and (2) problems with mental clutter. Example items for problems in cognition included trouble with "concentration", "memory", or "mental speed"; whereas mental clutter items included trouble with "spaciness", "fogginess, or "information overload." Research by Leavitt and Katz (2011) revealed that these two dimensions (8-items each) contained a good factor stability with an internal consistency of 0.95 when testing in two large samples (*n* = 128 and *n* = 170). After a median of 5 days, the test-retest reliability was 0.95. Moreover, the benefit of this scale is that it is brief. With irritation being a significant problem for some persons with TBI (Yang, Hua, Lin, Tsai, & Huang, 2012), utilizing a brief survey without compromising accuracy of measurement is preferred to avoid attrition. For this research, they combined the sub-scores of the two dimensions to obtain a score of general mental fog. The range of scores lies between 16 (no fog) and 160 (most severe mental fog). Leavitt and Katz (2011), found the mean score of a large sample (*n* = 170) of persons with fibromyalgia to be 50.0 (*SD* = 20.3) for Mental Clutter and 50.7 (*SD* = 20.2) for problems with cognition. In addition, they found high reliability for the total score (*α* = .95; Leavitt & Katz, 2011). In this study, we used the total score to provide an index of severity of the mental fog with higher values indicating greater cognitive difficulty. This exhibited high internal consistency across groups (*α*s range from .95 to .96).

Objective cognition.

Cogstate Brief Battery®

An objective evaluation of cognitive performance was obtained by the Cogstate Brief Battery® (Collie, Maruff, Darby, & McStephen, 2003; Pietrzak et al., 2008). This battery is derived from the general Cogstate Battery® which is comprehensive and tests several domains (see www.cogstate.com). However, for brevity the current two studies used the brief battery which only takes 10 to 15 minutes to complete. The Cogstate Brief Battery® consisted of four tests:

(1) The Detection task is a simple reaction time task in which participants must press a "YES" key (Letter K) when they see a card turned face-up on the screen. Maruff et al. (2009) found high construct validity with measures of processing speed time (Trails Making Task-A; *r* = .70).

(2) The Identification task is a choice-reaction time task in which participants must determine if a car is red or black and press the appropriate key. Maruff et al. (2009) found high construct validity with measures of processing speed accuracy (Symbol-Digit Substitution Task, *r* = .74).

(3) The One-Back task is an updating task like the n-back; in this task participants must select if the card presented to them is the same as the one just before. Maruff et al. (2009) found high construct validity to measure working memory capacity (Span task, *r* = .80).

(4) Lastly, in the Learning task, participants must select if a card presented has ever been presented in the deck before; this requires intact memory and learning ability. Maruff et al. (2009) high construct validity with measures of short-term memory (Brief Visual Memory Test, *r* = .83) and long-term memory (Rey Complex Figure Test-Delayed Recall, *r* = .79).

Each task has a set of 1 to 3-minute practice trials to ensure comprehension of the task. To ensure optimum performance, participants wore a headset for auditory performance feedback (e.g., which makes a harsh tone for wrong answers and a light sound for correct answers). Scores were calculated using a proprietary algorithm incorporating speed, accuracy, hits, misses, and anticipations.

Useful Field of View®

In addition to Cogstate®, Useful Field of View (UFOV®; Ball & Owsley, 1993) was also used to capture objective cognition. This measure has been used in adolescents (McManus, Cox, Vance, & Stavrinos, 2015), older adults (Clay et al., 2005), and persons with TBIs (Novack et al., 2006). UFOV® consists of four tasks capturing processing speed and forms of executive function (Daigneault et al., 2012; Schmidt et al., 2016; Whelihan et al., 2005):

(1) UFOV®1 – Stimuli Identification: Participants must quickly determine if they viewed a “car” or “truck” within milliseconds of exposure. This task captured speed of processing that has convergent validity with other processing speed measures such as Trails Making Task A (*r* = .51; Vance et al., 2006; Vance, Wadley, Crowe, Raper & Ball, 2011).

(2) UFOV®2 – Divided Attention: Participants shift between identifying a car or truck in the center and remembering the location of a car in the periphery. The location of the car in the periphery can occur anywhere on an eight-spoke spiral around the center stimuli. As named, this task estimated divided attention but partly captured set-shifting ability (*r* = .46; Vance et al., 2011); this is consistent with previous conceptions that set-shifting requires divided attention (Reitan, 1958).

(3) UFOV®3 – Selective Attention I: Participants complete the same task as UFOV®2 but now there is distracting stimuli (47 triangles) across the screen. Showing convergent validity, performance on UFOV®3 correlates moderately with inhibition measured by the Stroop effect (*r* = .63, Bell, Mirman, &

Stavrinos, 2018) or distractibility during simulated driving (Wood, Chaparro, Lacherez, & Hickson, 2012).

(4) UFOV®4 – Selective Attention II: The fourth subtest also tests selective attention in the presence of distractors (47 triangles) but with a new task involving the center stimuli. Participants must decide if two stimuli in the center are the same (two cars or two trucks shown) or different (car and truck shown) while determining the location of the peripheral car as before. Like UFOV®3, the fourth subtest also estimates selective attention (UFOV®3; Ball & Owsley, 1993) – a form of attentional inhibition (Friedman & Miyake, 2004; Houghton & Tipper, 1996). However, it involves the introduction of a novel task that increases difficulty.

Each subtest comprises visual demonstrations and a 2-minute practice to verify task comprehension. During performance, the software provides an exposure threshold at which 75% of responses are correct. These scores approximated optimal ability for each cognitive domain.

Depressed mood

The Profile of Mood States (POMS) captured depressive symptoms for both injury and healthy control groups. The POMS is a 37-item instrument that allows participants to denote feelings "since their injury" for the mild and moderate-to-severe TBI groups and "in the last two weeks" for healthy control group. Participants rated how frequently they experienced various symptoms using the following Likert-type scale: "1-not at all," "2-a little," "3-moderately," "4-quite a bit," and "5- extremely." This format provides a quickly answerable instrument with high factorial, face and construct validity (McNair, Lorr, & Droppleman, 1971). To control for between- (Aim 1) and within-group (Aim 2 and 3) differences in negative affect, we used the depression (POMS-Dep) subscale from this instrument. This subscale includes feelings of being unhappy, sad, hopeless, discouraged, miserable, helpless, and worthless. POMS-Dep scores range from 8 (no depressive symptoms) to 40 (severe depressive symptoms) with excellent internal consistency in the original (α = .95, Curran et al., 1995) and the current study (αs range from .88 to .94).

Post-Concussive Symptoms

The Post-Concussive Symptom Scale (Iverson et al., 2003) indexes post-concussive symptoms, a measure of injury severity or health problems. This instrument contains 22 various symptoms rated from 0 (no symptoms) to 6 (severe symptoms); symptoms include a 4-item cognitive domain, 14-item somatic domain, and 4-item mental domain. Responses are summed and range from 0 (no concussion symptoms) to 132 (high concussion symptoms) and show excellent internal consistency (α = .93, Lovell et al., 2006). For mild TBI, specifically, the scale can reliably measure injury recovery with decent test-retest reliability (Lovell et al, 2006; Iverson et al., 2003). In healthy controls, post-concussive-like symptoms are common (Iverson et al., 2003). Thus, we used the total score to control for medical symptoms not related to mild TBI. Previously literature shows that health screeners in typical adolescents can pick up Internal consistency of the total scale was high (αs range from .89 to .95).

Mild TBI study.

Participants were assessed within 2 weeks to confirm mild TBI and current valid driver's license. Once eligibility was confirmed, participants were scheduled for a 90-minute appointment before the end of the 2-week period. A consent form and packet of take-home questionnaires on pre-injury driving history and behavior were mailed to be completed before the appointment. At the time of their appointment, an experimenter obtained informed consent (if less than 18 years of age informed consent was obtained from parent and assent from participant) and acquired the take-home material. After performing tests of balance and visual acuity, participants completed the practice drive in which the experimenter introduced them to the vehicle and helped adjust to the simulator's controls. Participants then completed four drives that were randomized to control for direction of drive, order of distraction, and presence of an embedded hazard. After each drive participants were assessed for simulator sickness and if they would like to proceed. In addition, participants complete the NASA Load Index to rate how demanding the task was on cognitive, emotional, and physical domains. Between drives, participants had 10-minute breaks to complete questionnaires on post-concussive symptoms, physical function, health, mood, and mental fog (MCS). At the end the study, participants completed the Cogstate Brief Battery®, UFOV®, and answered the BIDSAM and questions on simulator sickness symptoms. For this study, participants returned 4-6 weeks later for a follow-up appointment in which the same procedure was repeated. For the current project, we will use only baseline data. After this appointment, all participants were mailed a $100 check for their time. Plus, will we use only the drive in which a distraction and an embedded hazard were not present, as these could heavily influence their typical speed control and lane maintenance abilities.

Moderate-to-severe TBI.

After referral, participants underwent telephone screening to confirm their eligibility in terms of grouping status (active driver versus non-driver), current valid driver's license, and physical capability to use simulator. A call confirmed group status with the referring physician or clinician. After confirming eligibility, participants were scheduled for a 90-minute laboratory appointment within the next 2 weeks. Just like the mild TBI group, they were mailed take-home questionnaires about their pre-injury driving history and driving behavior, quality of life, posttraumatic stress, and mood to be completed before the appointment. At the arrival of their appointment, experimenters obtained informed consent. An experimenter blind to their driving group status completed the driving assessment involving a practice drive and four scenarios completed in the same order. The drive without ambient traffic involved driving on a four-lane highway without other cars or distraction and the drive with ambient traffic encompassed driving on a four-lane highway with others traffic in the opposite and same lane while deciding if presented billboards contained reversed or typical letters. Similar to the Mild TBI study, participants had 10-minute breaks between drives to complete UFOV® and Cogstate Brief Battery® as well as other cognitive tasks and questionnaires on function and post-concussive symptoms. At the end of the appointment, participants completed the BIDSAM, an evaluation of their self-perceived driving difficulties, and were debriefed. Participants were then mailed a $75 check for participation. For this proposed project, used only the first and third drive in which an auditory distraction was not provided, as auditory distraction would hurt ecological validity by influencing their typical speed control and lane maintenance abilities. The first drive measured mechanical operation of a vehicle while the second measured performance with ambient traffic.

CHAPTER 4

STATISTICS DATA ANALYSIS

Data extraction and merging

Approved by the UAB Institutional Review Board, this study combined data from two pilot projects including “Fitness to Driving after Mild Traumatic Brain Injury among Teen Drivers” (#X160830007, PI: Dr. Despina Stavrinos) and “Simulated Driving Assessment for Individuals with TBI’s” (#X160907003, PI: Dr. Despina Stavrinos). Data collection began in August 2016 and ended June 2018. After this time, data was merged on demographics (gender, age, race, and ethnicity) and injury characteristics (post-concussive symptom severity at screening and baseline, days since injury, and mechanism). Next, driving history was combined from the driving history questionnaire on dates they received their permit and license as well as the number of MVCs (further separated into at-fault and not-at-fault) and tickets they have received in the last three years. Regarding our primary variables, individual and total scores on the MCS and BIDSAM alongside scores on UFOV® and Cogstate® tasks were added into a combined dataset. Simulator outcomes for the drives without auditory distraction and embedded hazards were added including metrics of speed control (*M* and *SD*), lane maintenance (*M* of lane position, *SD*), and crash count.

Preliminary analyses

We first calculated descriptive statistics including means and standard deviations on all variables using SPSS version 25 (IBM, 2018) shown in Tables 1 to 2. Variable distributions were then inspected for normality using histograms, Shapiro-Wilk tests of normality, indexes of skewness, and indexes of kurtosis. Lastly, we examined for outliers defined by observations three standard deviations away from the mean and we removed them during sensitivity analyses. Distributions found to be non-normal informed our use of non-parametric analyses or ones that can fit an obvious non-Gaussian distribution or assume no underlying distribution. Distributions also informed if we would transform data; however, method of analyses were robust to violations in assumption and transformation would greater harm interpretation. We reported *p*-values and effect sizes for all analyses and determined significance at the .05 level and marginal significance at the .10 level.

Primary analysis

AIM 1: To compare severity of mental fog in mild and moderate-to-severe TBI to healthy controls.

We examined the effect of group (control, mild TBI, and moderate-to-severe TBI) on the continuous measure of mental fog (MCS total) using ANOVA. If provided a significant omnibus test, Tukey's post-hoc tests were then conducted to determine pairwise differences (control versus mild TBI, control versus moderate-to-severe TBI, mild TBI versus moderate-to-severe TBI). Because of the small sample design and possible non-normality of mental fog, this was followed by a Kruskal–Wallis test which inspected group differences based on rank. A sensitivity analysis using ANCOVA then tested if group differences in mental fog were independent of group differences in depressive symptoms (POMS-Dep).

AIM 2: To examine if mental fog reflects problems in objective cognitive performance after mild and moderate-to-severe TBI involving measures of processing speed, executive function, and memory.

The total relationship between mental fog (MCS total) on continuous measures of objective cognition (processing speed time, processing speed accuracy, updating, and memory) were tested using Pearson correlations in the mild TBI, moderate-to-severe TBI, and healthy control groups, separately. If non-normal, then we conducted non-parametric Spearman rank correlations. Pearson or Spearman rank correlations were partialled to adjust for depressive symptoms, our covariate of interest. Separate results are shown for each group.

AIM 3: To test if mental fog relates to driving outcomes after mild and moderate-to-severe TBI involving simulated driving performance, MVCs, and self-rated driving performance.

If normally distributed, the relationships between mental fog (MCS total) on continuous measures of simulated driving performance (average and standard deviation of speed and lane position) and self-reported driving difficulty (BIDSAM) were tested using linear regression analysis. If non-normality was shown with an obvious non-Gaussian distribution, a general estimating equation might fit the appropriate distribution;

otherwise, we applied nonparametric Spearman rank correlations that assume no underlying distributions. Any models controlled for driving experience and objective cognition, covariates of interest. Also, as a primary analysis, we controlled for other potential variables if related to mental fog or diving outcomes; potential covariates included age, gender, and injury severity (time since injury and post-concussive symptom severity). Due to differing scenarios used between studies, simulator data between mild TBI and moderate-to-severe TBI cannot be compared directly. Thus, we reported separate results for the mild TBI, moderate-to-severe TBI, and healthy controls.

CHAPTER 5

RESULTS

Participant Characteristics

Demographics and driving history

Participant demographics and driving history are shown in Table 1. For the mild TBI group (n = 15), the average participant age was 16.06 years (SD = 0.80, range: 16 to 19). This group was predominately female (60.0%, n = 9) and Caucasian (80.0%, n = 12) with approximately a year elapsed since licensure (M = 11.41 months, SD = 8.67, range = 1.77 to 30.16). Regarding driving history from the last three years, the police pulled over four persons and issued a ticket to two of these participants. A small portion of the sample reported an MVC (26.7%, n = 4) in the last three years, where one claimed at fault (6.7%).

The healthy control group (n = 16) appeared successfully matched to the mild TBI group on demographics and driving history. The average participant age was 17.06 years (SD = 1.57, range: 16 to 22) which did not statistically differ from the mild TBI group ($t(29) = .73$; $p = .472$). This group was also predominantly female (62.5%, n = 16) and Caucasian (75.0%, n = 12), indistinguishable from the mild TBI group on sex ($X^2(2) = .02$, $p = .886$) and race proportions ($X^2(2) = 1.64$, $p = .441$). This group also exhibited similar driving experience with an average of 15.22 months elapsed since licensure; this was statistically indifferent from the mild TBI group ($t(29) = .77$, $p = .449$). Regarding previous three-year driving history, police pulled over (31.3%, $n = 5$, $X^2(2) = 1.42$, $p = .491$) and issued tickets to a similar number of participants (6.3%, $n = 1$, $X^2(2) = .22$, $p = .642$). Lastly, participants had a similar occurrence of MVCs in the last three years (43.7%, $n = 7$, $X^2(2) = 1.33$, $p = .513$) with four individuals at fault (25.0%).

Exceeding our original recruitment goal, our moderate-to-severe TBI group consisted of 15 participants. These individuals were predominately young to middle-aged adults ($M_{age} = 33.19$ years, $SD = 8.74$, range = 20 to 50) – significantly older than our mild TBI and control samples ($F(2,43) = 51.72$, $p < .001$, $\eta^2 = .71$). The sample consisted of a slight male majority (56.3%, $n = 9$) and were mostly Caucasian (75.0%, $n = 12$). The moderate-to-severe TBI group were similar on sex ($X^2(2) = 1.33$, $p = .514$) and race proportions ($X^2(2) = .20$, $p = .905$) compared to the mild TBI and healthy control groups. As expected from older age, this group had several months of driving experience ($M = 214.69$ months since licensure, $SD = 101.58$) higher than other groups ($F(2,43) = 58.68$, $p <.001$, $\eta^2 = .73$) but did not differ on the number of individuals pulled over (33.4%, $n =5$; $X^2(2) = .17$; $p = .921$), received a ticket (26.7%, $n = 4$, $X^2(2) = 2.26$, $p = .278$, or incurred a general MVC (46.7%, $n = 7$; $X^2(2) = 2.78$, $p = .249$) or at fault MVC in the last three years (13.3%, $n = 2$, $X^2(2) = 2.08$, $p = .354$).

Table 1. Participant Demographics and Driving Characteristics.

	Healthy Controls [a] n = 16		Mild TBI [b] n = 15		Moderate-to-severe TBI [c] n = 15					
	M/%	*SD*/*n*	*M*/%	*SD*/*n*	*M*/%	*SD*/*n*	X^2/ANOVA *p*-value	a vs. b	a vs. c	b vs. c
Demographics										
Gender							.514			
Female	62.5	10	60	9	43.8	7				
Male	37.5	6	40	6	56.3	9				
Race								.441		
Caucasian	75.0	12	80.0	12	73.3	11				
African American	25.0	4	13.3	2	26.7	4				
Asian	0.0	0	0.0	0	0.0	0		.513		
Bi-racial	0.0	0	6.7	1	0.0	0				
Age (years)	17.06	1.57	16.73	0.80	33.19	8.74	<.001	.472	<.001	<.001
Time Since Injury (mo.)	–	–	0.40	0.13	44.26	36.84	<.001			
Driver History										
Months since licensure	15.22	17.27	11.41	8.67	214.59	101.58	<.001	.449	<.001	<.001
Pulled Over Last 3 Years#	31.3	5	28.6	4	33.4	5	.921			
Ticket Last 3 Years#	6.3	1	13.3	2	26.7	4	.278			
MVC Last 3 Years#	43.7	7	26.7	4	46.7	7	.249			
At-fault MVC Last 3 Years#	25.0	4	6.7	1	13.3	2	.354			

Notes. MVC = Motor vehicle collisions. Boldened variables indicate significant differences. #outcome is binary (yes/no)

Shared study measures

Table 2 shows shared study outcomes between groups including mental fog, objective cognitive tasks, and self-reported driving ability. Mental fog differences are discussed later in Aim 1 results. Regarding objective cognition indexed by UFOV®, groups did not differ significantly on speed of processing (UFOV®1; $F(2,43) = 2.14$, $p = .130$). However, significant differences emerged for UFOV®2 ($F(2,43) = 6.14$, $p = .005$, $\eta^2 = .22$), UFOV®3 ($F(2,43) = 9.82$, $p < .001$, $\eta^2 = .31$), and UFOV®4 ($F(2,43) = 13.94$, $p < .001$, $\eta^2 = .39$). Specifically, individuals with moderate-to-severe TBI exhibited worse divided attention (UFOV®2: $d = .66$) and selective attention compared to the mild TBI (UFOV®3: $d = .90$; UFOV®4: $d = 1.00$) and healthy controls (UFOV®3: $d = 1.61$; UFOV®4: $d = 2.20$). Though not significantly different on other UFOV® tasks, the mild TBI group showed marginally greater difficulty in selective attention indexed by UFOV®4 than healthy controls ($p = .091$, $d = .73$). After generalized linear models accounted for differences in age, group differences remained only for UFOV®4 only ($F(2,42) = 3.27$, $p = .049$); no significant age effects occurred, however (*p*s > .25).

On the Cogstate® instrument, groups significantly differed on processing speed captured by the Detection ($F(2, 43) = 5.19$, $p = .010$, $\eta^2 = .19$) and Identification tasks ($F(2,43) = 5.29$, $p = .009$, $\eta^2 = .23$). Primarily, individuals with mild TBI processed information slower than healthy controls on the Detection task ($p = .011$; $d = 1.07$). Whereas, persons with moderate-to-severe TBI performed significantly worse on the Identification task than healthy controls ($p = .008$, $d = 1.38$). No significant differences in processing speed appeared between mild and moderate-to-severe TBI (*p*s >.50).

Secondly, groups significantly differed on updating ability indexed by the One Back task (F(2,43) = 4.53, p = .0164, η^2 = .17; 95%CI[.01 to .35]). Mild TBI and their healthy counterparts did not differ on updating (p = .611), but healthy controls performed better updating than individuals with moderate-to-severe TBI (p = .013, d = 1.26). No group differences were shown in memory indexed by the Learning task (F(2,43) = 1.79, p = .179). All group effects remained significant after generalized linear models corrected for age differences (ps < .05); no significant age effects occurred (ps > .14).

Self-reported measures shared across studies quantified post-concussive symptoms, depressed mood, and perceived driving ability. Groups significantly differed on post-concussive symptoms (F(2,43) = 3.24, p = .049, η^2 = .13) with healthy controls reporting lower symptoms than moderate-to-severe TBI (p = .039, d = .96); both groups of TBI were indistinguishable (p = .545). Meanwhile, groups reported similar depressive symptoms (F(2,43) = .79, p = .459). Lastly, there was a significant difference on perceived driving difficulty (F(2,43) = 3.89, p = .028, η^2 = .15) such that individuals with mild TBI reported greater troubles in simulated driving than those with moderate-to-severe TBI (p = .024, d = .92).

Table 2. Shared Study Outcomes.

	Healthy Controls[a] *n* = 16		Mild TBI[b] *n* = 15		Moderate-to-severe TBI[c] *n* = 15					
	M/%	*SD*/*n*	*M*/%	*SD*/*n*	*M*/%	*SD*/*n*	ANOVA *p*-value	a vs b	a vs c	b vs c
UFOV®										
UFOV®1 - Speed of Processing	17.00	0.00	30.29	48.95	47.87	54.06	.130			
UFOV®2 - Divided Attention	17.38	1.50	52.63	101.99	119.13	100.74	.005	.202	.004	.073
UFOV®3 - Selective Attention I	52.00	24.82	99.33	114.38	215.00	141.36	<.001	.117	<.001	.012
UFOV®4 - Selective Attention II	94.63	58.25	173.42	141.46	306.20	123.08	<.001	.091	<.001	.007
Cogstate®										
Detection	99.67	4.08	89.29	13.15	91.60	9.17	.010	.011	.057	.783
Identification	102.81	5.12	95.8	11.16	92.53	9.86	.009	.089	.008	.585
Learning	101.69	7.66	95.13	12.26	98.40	8.52	.179			
One Back	95.25	6.76	94.07	10.61	87.13	6.12	.016	.913	.020	.058
MCS	38.56	21.39	63.20	29.43	73.40	32.96	.004	.014	.004	.587
Mental Clarity	17.81	10.31	31.73	15.89	32.73	19.23	.016	.008	.027	.983
Cognitive Problems	20.75	11.42	31.47	14.44	40.67	16.13	.001	.031	.001	.185
PCSS	19.94	15.66	30.67	22.54	38.60	22.84	.049	.133	.039	.545
POMS-Dep	14.06	6.14	14.27	5.40	16.67	7.37	.459			
BIDSAM total	23.94	6.58	26.73	10.31	18.53	7.31	.028	.372	.170	.024

Notes. BIDSAM = Brain Injury Self-Awareness Scale; MCS = Mental Clutter Scale; PCSS = Post Concussive Symptom Scale; POMS-Dep = Depression subscale from Profile of Mood States; UFOV® = Useful Field of View. Bold variables indicate significant differences, $p < .05$.

Data characteristics

Across groups, little missingness occurred. For healthy controls, no data was missing. For the mild TBI group, missingness occurred for one person on the Cogstate® task where the program could not compute a Detection task score. This person was not an outlier on any demographic or variable listed in Tables 1 and 2. It appeared they were pressing a wrong key which invalidated responses for score calculation. Scores generated for the other subtests as it appeared the participant learned the correct keys. The average and variation in speed for the ambient traffic drive were incalculable for three participants with moderate-to-severe TBI; the data reduction program was unable to compute the speed due to unresolvable errors in the data file (i.e., impossible nonnumerical values). These three were not statistically different on any demographic or shared variables (*p*s > .10); plus, we still met our recruitment goal of 12 cases for these variables.

While little data was missed, many variables were non-normally distributed. For the healthy controls, data was non-normally distributed for mental fog, depressive symptoms, driving experience, age, BIDSAM totals, speed (*M* and *SD*), and Identification, and UFOV®2 scores (Shapiro-Wilk values range: .62 to .88, *p*s < .05). For the mild TBI group, Shapiro-Wilk tests were significant for depressive symptoms, age, *SD* of speed, total collisions, and all UFOV tasks (Shapiro-Wilk values range: .31 to .88, *p*s < .05). Within the moderate-to-severe TBI group, we observed non-normality for UFOV®1, BIDSAM scores, *M* and *SD* lane position for ambient traffic drive, and total collisions in ambient traffic drive (Shapiro-Wilk values range: .52 to .88, *p*s < .05).

Looking at skewness and kurtosis values, most variables stayed within the appropriate cut offs (± 2); this indicates mild non-normality.

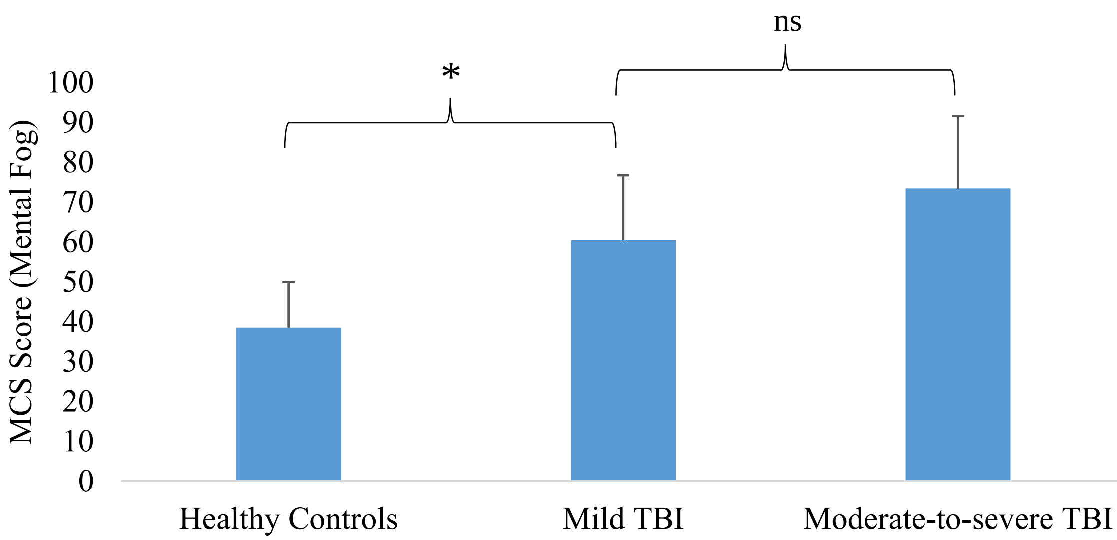
Regarding outliers in the healthy control group, one participant's age and driving experience was beyond three standard deviations away from the mean. In addition, one control exhibited severe mental fog that was three standard deviations away from the mean. For the mild TBI group, one person exceeded 3 standard deviations away from the normal standard deviation of speed; another person exceeded 3 standard deviations away from the average number of total collisions. Meanwhile, one participant did abnormally worse on the UFOV® 1-3 task than others in the group. For the moderate-to-severe group, one person had an unusually high amount of collisions for the ambient traffic drive that exceeded our cutoff as an outlier. Nonetheless, results described below were not influenced by these outliers; the same pattern of results was shown when removing them. Thus, subsequent analysis included all participants.

Overall, we successfully collected most data, though not all, derived from a normal sampling distribution; plus, there were some outliers. Variable characteristics then guided the appropriate methods to proceed with statistical testing. Transforming data to improve normality did not appear suitable: One, it would harm interpretability considerably; two, there were only mild violations in normality (which could remain after transformations). Instead, we applied statistical frameworks robust to normality violations. This included ANOVA for Aim 1 and nonparametric Spearman rho correlations for Aim 2. Due to considerable outliers and no meaningful, non-Gaussian distributions across simulator outcomes, we also decided to use Spearman rho correlations in place of GEE estimation for Aim 3. Unlike GEE, Spearman rho correlations are appropriate for small sample designs and are robust against outliers. Notwithstanding, even when attempting GEE estimation, most models fit the data poorly or were unable to converge. Lastly, to adjust for covariates, we used ANCOVA or generalized linear models for Aim 1 and partial Spearman rank correlations (Liu et al., 2016) for Aim 2 and 3.

AIM 1

After conducting a one-way ANOVA, we found a significant effect of group on mental fog ($F(2,43) = 6.29$, $p = .004$; $\eta^2 = .23$; 95%CI[.03 to .40]). Post-hoc tests confirmed that individuals with mild TBI reported higher mental fog compared to healthy controls ($M_{\text{Diff..}} = 24.64$, $p = .019$; 95%CI[4.19 to 45.08]; $d = .96$; 95%CI[.20 to 1.68]). However, there was no significant difference in mental fog between individuals with mild TBI and moderate-to-severe TBI ($M_{\text{Diff..}} = 10.20$, $p = .327$, 95%CI[10.57, 30.97]). As part of sensitivity analysis on rank differences, a nonparametric Kruskal-Wallis test still showed a significance difference between groups ($p = .006$). Next, after an ANCOVA adjusted for depressed mood, there remained a significant effect of group on mental fog ($F(2,42) = 5.85$, $p = .006$; $d = .22$, 95%CI[.02 to .39]) independent of differences in depressive symptoms ($F(1, 42) = 9.79$, $p = .003$, $\eta^2 = .19$; 95% CI[.02 to .38]).

Figure 1. Group differences on mental fog.



AIM 2

Healthy controls

As shown in Table 3, mental fog did not associate with any scores on UFOV® or Cogstate® in healthy controls ($|rs_{sp}|$ range: .04 to 42, all *p*s > .10). Although greater mental fog reflected worse divided attention after controlling for depressive symptoms (r_{sp} = .57, *p* = .044). Upon further inspection, this might derive from a restricted range as most people performed perfectly on UFOV®2; the one person without a perfect score had high depressive symptoms.

Table 3. Correlations between Mental Fog and Objective Cognitive Tasks in Healthy Controls (*n* = 16).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. MCS	1.00	.65**	.57*	.11	-.38	.10	.08	-.15	-.25	0	.36	.35	.34
2. POMS-Dep		1.00	.81**	-.04	-.34	.24	.29	-.13	-.22	0	-.03	.15	.12
3. PCSS			1.00	-.08	-.49†	.19	-.01	-.17	-.06	0	.08	.10	.05
4. Age				1.00	-.23	.22	.13	-.17	-.13	0	.33	-.08	.31
5. Sex					1.00	-.10	-.10	.07	-.02	0	-.20	-.25	-.42
6. Detection						1.00	.67*	.33	.53**	0	-.03	-.22	-.29
7. Identification							1.00	.44	.27	0	-.19	.24	-.05
8. Learning								1.00	.07	0	-.16	-.25	-.43
9. One Back									1.00	0	-.19	-.14	-.35
10. UFOV®1										1.00	0	0	0
11. UFOV®2											1.00	.06	.42
12. UFOV®3												1.00	.59*
13. UFOV®4													1.00

Notes. All correlations are Spearman rho. MCS = Mental Clutter Scale; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States; UFOV = Useful Field of View. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Mild TBI

We calculated Spearman rank correlations between mental fog and objective cognition after mild TBI, as shown in Table 4. For individuals with mild TBI, higher mental fog corresponded to slower speed of processing (UFOV®1; $r_{sp} = .63$, $p = .012$) but unrelated to all other measures ($|rs_{sp}|$ range: .02 to .35, *p*s > .20). Next, we partialled out the effect of depressive symptoms from these correlations. This covariate appeared relevant as higher depressive symptoms related to higher mental fog ($r_{sp} = .66$, $p = .008$); although depression was unrelated to objective cognition ($|rs_{sp}|$ range: .02 to .23, *p*s > .40). After removing the impact of depressive symptoms, the relationship between mental fog and speed-of-processing was now insignificant ($r_{sp} = .25$, $p = .488$). This corrected estimate was nearly half of the original suggesting that depressive symptoms biased the relation between mental fog and speed of processing.

Table 4. Correlations between Mental Fog and Objective Cognitive Tasks in Mild TBI (*n* = 15).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. MCS	1.00	.66**	.67**	.29	.12	-.35	.31	-.02	-.30	.06	.63*	.35	.26	.18
2. POMS-Dep		1.00	.73**	.33	.29	-.46†	-.44	-.05	-.39	-.17	.22	.02	.25	.45
3. PCSS			1.00	.18	.32	-.24	-.41	.12	-.47†	.09	.56*	.22	.35	.50
4. Time Since Injury				1.00	-.03	-.32	-.58*	-.65**	-.10	-.42	.37	.65**	.36	.39
5. Age					1.00	.04	.18	.35	.06	.25	.02	.03	.43	.12
6. Sex						1.00	.61*	.32	-.25	.49	-.26	-.22	-.43	-.22
7. Detection							1.00	.69**	.18	.55*	-.48†	-.51†	-.33	-.77**
8. Identification								1.00	.09	.65**	-.21	-.51†	-.12	-.42
9. Learning									1.00	.13	-.10	-.02	.27	-.19
10. One Back										1.00	-.16	-.30	-.49	-.56†
11. UFOV®1											1.00	.82***	.45†	.48
12. UFOV®2												1.00	.41	.30
13. UFOV®3													1.00	.57†
14. UFOV®4														1.00

Notes. All correlations are Spearman rho. MCS = Mental Clutter Scale; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States; UFOV = Useful Field of View. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Moderate-to-severe TBI

Spearman rank correlations examined the total effects of mental fog on objective cognition in moderate-to-severe TBI, seen in Table 5. Greater mental fog related to slower processing speed indexed by lower scores on the Detection task ($r_{sp} = -.55$, $p = .033$). Also, mental fog also negatively related to memory ($r_{sp} = -.55$, $p = .034$) and updating ($r_{sp} = -.68$, $p = .006$) indexed by lower scores on the Learning and One Back tasks, respectively (see Figure 2 and 3). Greater mental fog severity marginally associated with slower processing speed indexed by lower scores on the Identification task ($r_{sp} = -.51$, $p = .053$).

Next, partial Spearman correlations adjusted for the impact of depressive symptoms. Greater depressive symptoms related to worse scores on the Identification task ($r_{sp} = -.66$, $p = .007$) in the moderate-to-severe TBI group ($r_{sp} = -.66$, $p = .007$), supporting the role of depressive symptoms as a covariate analysis in subsequent calculations. Higher depressive symptoms were unrelated to mental fog ($r_{sp} = .26$, $p = .349$), however. After controlling for depressive symptoms, greater mental fog significantly related to worse scores on the Learning ($r_{sp} = -.57$, $p = .033$) and One Back task ($r_{sp} = -.65$, $p = .013$; see Figures 2 and 3). In addition, mental fog marginally reflected worse processing speed indexed by the Detection ($r_{sp} = -.51$, $p = .064$) and Identification task ($r_{sp} = -.47$, $p = .094$).

Figure 2. Correlation between Mental Fog and the Cogstate® Learning task in moderate-severe TBI.

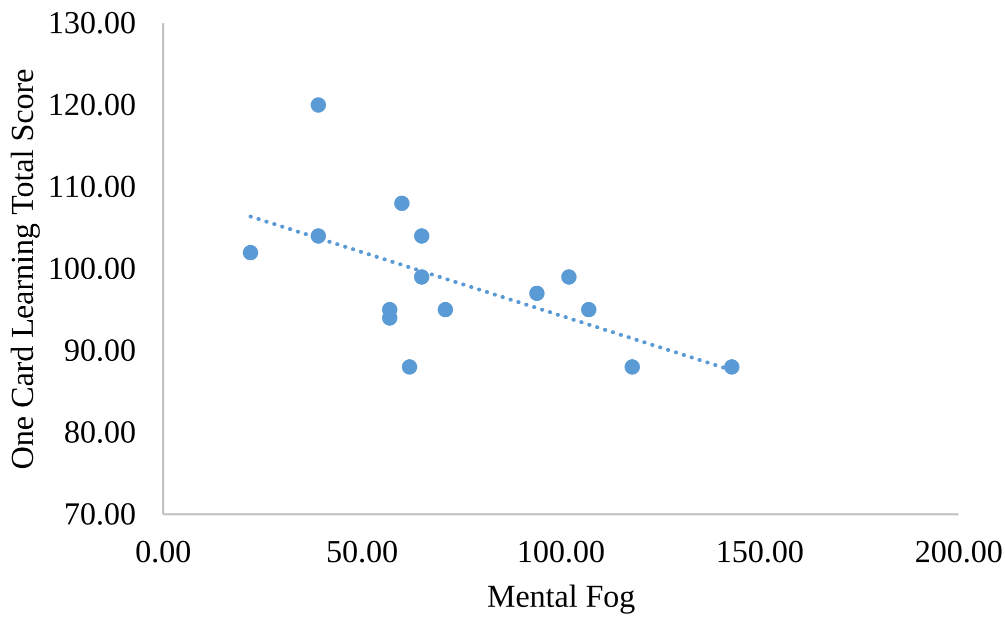


Figure 3. Correlation between Mental Fog and the Cogstate® One Back task in moderate-severe TBI.

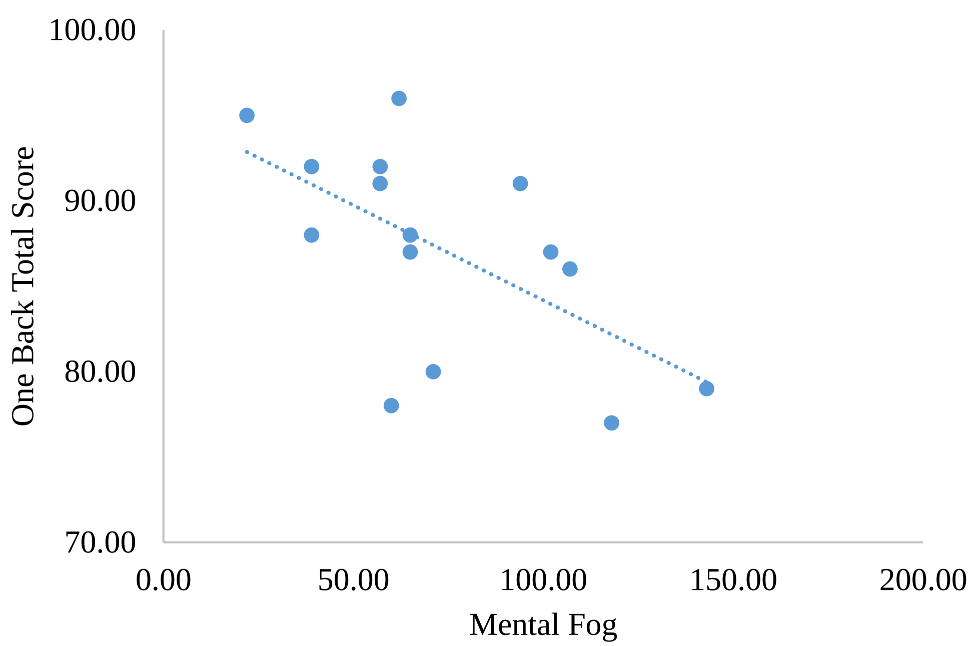


Table 5. Correlations between Mental Fog and Objective Cognitive Tasks in Moderate-to-severe TBI (n = 15).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. MCS	1.00	.26	.07	-.03	-.16	.13	$-.55^{*}$	$.51^{\dagger}$	$-.55^{*}$	$-.68^{**}$	.15	.05	-.13	-.28
2. POMS-Dep		1.00	$.50^{\dagger}$	-.39	.29	.02	-.37	$-.66^{**}$	.00	-.35	.21	.15	.42	-.01
3. PCSS			1.00	-.25	.30	.09	-.13	-.31	.20	-.20	.27	.09	.23	-.12
4. Time since injury				1.00	.18	.13	.01	.32	-.03	.10	-.27	-.29	-.32	-.24
5. Age					1.00	.24	-.12	.09	-.02	.40	-.13	-.09	.13	.10
6. Sex						1.00	.30	-.16	-.14	-.16	.15	.17	.06	.17
7. Detection							1.00	$.46^{\dagger}$	.36	.08	-.30	-.10	-.18	.19
8. Identification								1.00	.25	$.69^{**}$	-.28	-.24	-.28	.05
9. Learning									1.00	.13	$-.58^{*}$	-.39	-.14	-.19
10. One Back										1.00	.13	-.03	.04	.29
11. UFOV®1											1.00	$.80^{***}$	$.66^{**}$	$.62^{*}$
12. UFOV®2												1.00	$.80^{***}$	$.77^{***}$
13. UFOV®3													1.00	$.68^{**}$
14. UFOV®4														1.00

Notes. All correlations are Spearman rho. MCS = Mental Clutter Scale; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States; UFOV = Useful Field of View. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

AIM 3

Healthy controls

Spearman rank correlations elucidated relations between healthy controls' mental fog and driving performance, seen in Table 6. Regarding total effects, mental fog did not reflect capabilities in simulated driving ($|rs_{sp}|$ range: .01 to .26, ps > .10). Instead, greater mental fog related to higher self-rated driving difficulty indexed by BIDSAM scores (r_{sp} = .55, p = .026; see Figure 4). Next, we sequentially controlled for driving experience and objective cognition as important covariates of interest. While driving experience dissociated with driving variables ($|r_{sp}|$ range: .02 to .43. ps > .05), better objective cognition marginally corresponded to fewer deviations in speed and lane position (both rs_{sp} = .45, p = .080). After adjustment for months since licensure, mental fog remained unrelated to simulated driving ability ($|rs_{sp}|$ range: .03 to .24, ps > .10) but positively correlated with self-rated driving difficulty (r_{sp} = .54, p = .037). After controlling for objective cognition, mental fog did not relate to simulated driving outcomes ($|rs_{sp}|$ range: .12 to .37, ps > .10) and marginally related to self-rated driving difficulty (r_{sp} = .51, p = .054).

Sensitivity analysis

To clarify the unique contribution of mental fog to driving, we controlled for other potential covariates such as demographics, injury symptoms, and depressive symptoms. Overall, males reported significantly lower difficulties on BIDSAM (r_{sp} = -.78, p = .002), greater speed variation (r_{sp} = .63, p = .022), and greater lane deviation (r_{sp}

= .70, p =.008). Older age related to higher average speed (r_{sp} = .77, p = .002). After controlling for these potential influential factors (sex, age, post-concussive symptoms, and depressive symptoms), there again remained no relation between mental fog and simulated driving outcomes ($|rs_{sp}|$ range: .01 to .31, ps > .20). When controlling for age, post-concussive symptoms, or depressive symptoms, the relationship between mental fog in self-rating driving remained positive and significant (rs_{sp} range: .53 to .56, ps < .05). Controlling for sex or post-concussive symptoms, however, made this effect marginal with some reduction in magnitude (r_{sp} range: .45 to .48, ps < .10).

Figure 4. Correlation between Mental Fog and BIDSAM scores.

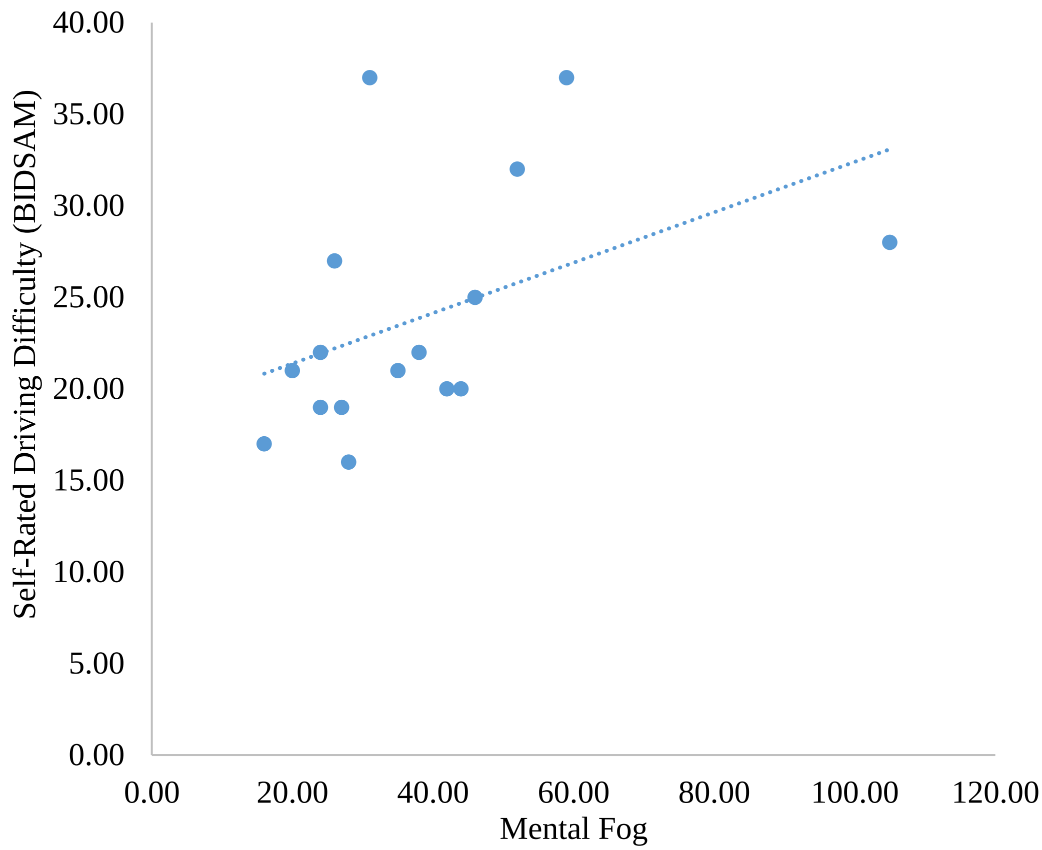


Table 6. Correlations between Mental Fog and Simulated Driving Ability in Healthy Controls (n = 16).

	1	2	3	4	5	6	7	8	9	10	11	12
1. MCS	1.00	-.27	$.65^{**}$	$.57^{*}$	.11	.13	-.38	.26	.01	.12	-.20	$.55^{*}$
2. Obj. Cognition		1.00	-.04	-.07	-.18	-.26	.08	-.11	$-.45^{\dagger}$	.12	$-.45^{\dagger}$	-.37
3. POMS- Dep			1.00	$.81^{**}$	-.04	-.02	-.34	.07	-.22	-.08	-.27	.26
4. PCSS				1.00	-.08	.08	$-.49^{\dagger}$	-.02	-.36	-.20	-.17	.31
5. Age					1.00	$.79^{**}$	-.23	.20	.05	-.09	-.05	$.43^{\dagger}$
6. Driving Experience						1.00	-.28	.43	.32	-.03	.26	.32
7. Sex							1.00	-.22	.01	-.28	.25	$-.79^{**}$
8. *M* Speed								1.00	$.66^{**}$	-.07	.26	.35
9. *SD* Speed									1.00	.21	$.52^{*}$	.18
10. *M* Lane Pos.										1.00	-.35	.06
11. *SD* Lane Pos.											1.00	-.18
12. BIDSAM												1.00

Notes. All correlations are Spearman rho. BIDSAM = Brain Injury Driving Self-Awareness Measure; MCS = Mental Clutter Scale; Lane Pos. = Lane Position; Obj. Cognition = Objective Cognition composite; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Mild TBI

Mental fog did not significantly associate with any simulated driving metric in mild TBI (|*r*s$_{sp}$| range: .07 to .20, *p*s >.40) (Table 7). Similar to healthy controls, a strong positive association between mental fog and self-reported driving ability emerged (r_{sp} = .82, p < .001; see Figure 5), suggesting that perceived cognitive problems and a lack of mental clarity accompanied worse self-rated driving. For the second step, partial correlations removed potential effects from driving experience even though driving experience was unrelated to all driving outcomes (|*r*s$_{sp}$| range: .01 to .31, *p*s > .20). Relations between mental fog and driving remained nonsignificant (|*r*s$_{sp}$| range: .03 to .14, *p*s > .60). After adjusting for years since licensure, a large positive link remained between mental fog and self-reported driving ability (r_{sp} = .82, p < .001). This magnitude is comparable to the total effect suggesting that differences in driving experience did not bias our estimate.

Lastly, we adjusted Spearman correlations to account for the impact of objective cognition on driving performance. Objective cognition indexed from UFOV® and Cogstate® was unrelated all simulated driving outcomes (|*r*s| range: .01 to .32, *p*s > .30) but better objective cognition significantly related to less self-reported driving difficulty (r_{sp} = -.55 p = .035). After controlling for objective cognition, there remained no significant effect of mental fog on simulated driving metrics (|*r*s$_{sp}$| range: .05 to .25, *p*s > .30). Greater mental fog still positively related to self-rated driving difficulties independent of objective cognition (r_{sp} = .82, p < .001). This relationship is similar in magnitude to the total effect suggesting that differences in objective cognition did not bias our estimate.

Sensitivity analysis

To identify other possible covariates for sensitivity analysis, we explored the relations between mental fog and driving with other mild TBI participant characteristics such as age, sex, depressive symptoms, post-concussive symptoms, and time since injury as well as drive order. Overall, mental fog positively linked with depressive symptoms ($r = .66$, $p = .008$) and post-concussive symptoms ($r_{sp} = .67$, $p = .007$). Male sex was associated with higher speed ($r_{sp} = .54$, $p = .040$). Greater post-concussive symptoms also related to greater self-reported driving difficulties ($r_{sp} = .56$, $p = .031$) as did depressive symptoms ($r_{sp} = .69$, $p = .004$). Age, driving experience, time since injury, and drive order were unrelated to all driving outcomes ($|rs_{sp}|$ range: .01 to .27, ps > .30). These results guided our sensitivity analysis to control for participant's sex, post-concussive symptoms, and depressive symptoms.

After controlling for participant's sex, post-concussive symptoms, or depressive symptoms, there remained no significant effect of mental fog on simulated driving metrics ($|rs_{sp}|$ range: .08 to .30, ps > .20). Furthermore, there remained a significant positive and moderate association between greater mental fog and higher self-reported driving difficulties ($|rs_{sp}|$ range: .66 to .79, ps <.05).

Figure 5. Correlation between Mental Fog and BIDSAM scores.

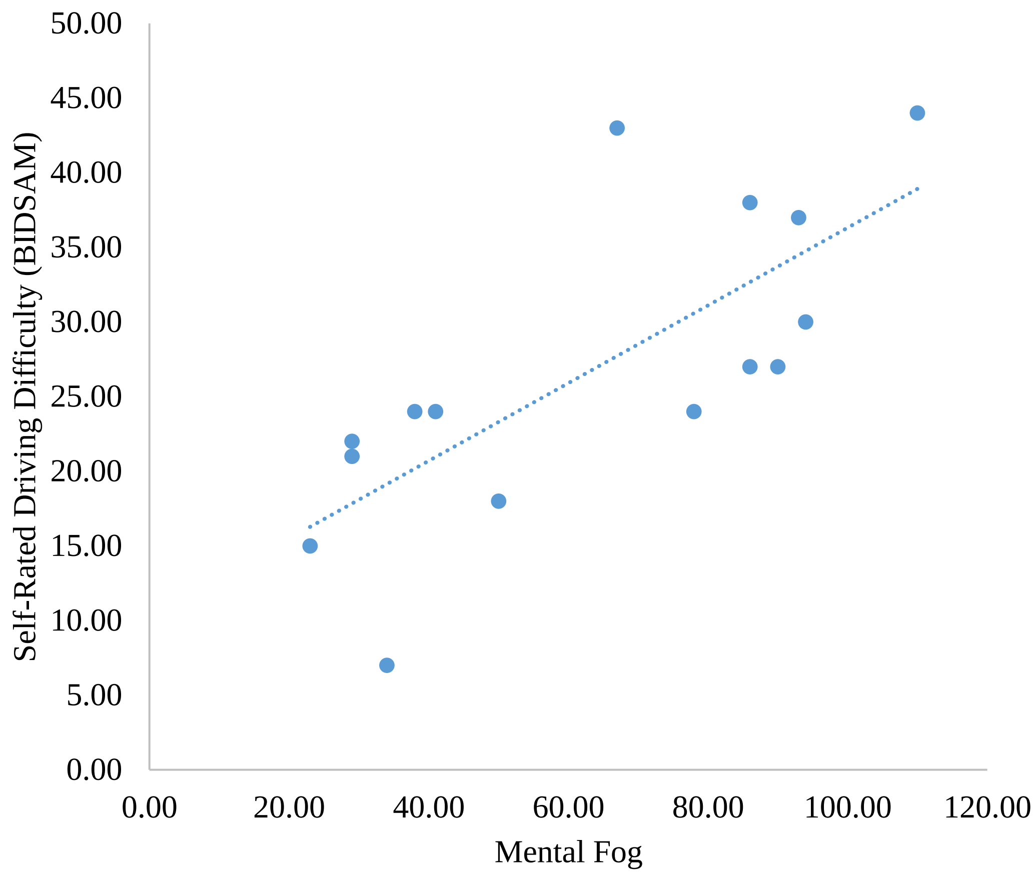


Table 7. Correlations between Mental Fog and Simulated Driving Ability in Mild TBI.

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. MCS	1.00	-.29	.66**	.67**	.12	.23	-.35	.20	.05	-.08	.07	.16	.82**
2. Obj. Cognition		1.00	-.39	-.40	.30	.40	.38	-.15	.02	-.16	-.16	.31	-.55*
3. POMS-Dep			1.00	.73**	.29	.36	-.46†	.02	.17	.17	-.03	.22	.69**
4. PCSS				1.00	.32	.27	-.24	.10	.19	.08	-.13	-.06	.56*
5. Age					1.00	.78**	.04	.11	.36	-.24	-.11	.17	-.11
6. Driving Experience						1.00	-.13	.31	.08	-.12	-.01	.19	.09
7. Sex							1.00	-.22	.54*	-.28	.19	-.22	-.46†
8. *M* Speed								1.00	-.37	-.28	.64*	-.31	.15
9. *SD* Speed									1.00	-.20	.01	.37	.02
10. *M* Lane Pos.										1.00	-.18	.12	.05
11. *SD* Lane Pos.											1.00	-.19	.22
12. MVCs												1.00	.09
13. BIDSAM													1.00

Notes. All correlations are Spearman rho. BIDSAM = Brain Injury Driving Self-Awareness Measure; MCS = Mental Clutter Scale; Lane Pos. = Lane Position; Obj. Cognition = Objective Cognition composite; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Moderate to Severe TBI

Spearman rank correlations examined the effect of mental fog on simulated and self-rated driving performance among individuals with moderate-to-severe TBI (Table 8). Regarding speed control, participants with greater mental fog drove faster around ambient traffic ($r_{sp} = .64$, $p = .026$; see Figure 6). Secondly, greater mental fog marginally related to greater left-hand deviation from the lane center during the drive with ambient traffic ($r_{sp} = -.44$, $p = .099$). Mental fog did not reflect other simulator metrics in drives with and without ambient traffic ($|rs_{sp}|$ range: .03 to .23, all *p*s > .40) or self-rated driving performance ($r = .39$, $p = .146$).

For our second step, we adjusted Spearman correlations to account for the impact of driving experience. Overall, driving experience was unrelated to any driving outcome in this group. Nonetheless, after adjustment, the impact of mental fog on average speed in the ambient traffic drive remained significant ($r_{sp} = .62$, $p = .043$). Regarding lane maintenance, a marginal effect of mental fog on average lane position with similar magnitude ($r_{sp} = -.47$, $p = .089$) remained irrespective of driving experience.

Next, we adjusted for objective cognition, our second covariate of interest. This covariate appeared important as better objective cognition reflected less speed deviation with ambient traffic ($r_{sp} = .74$, $p = .006$) and marginally less lane deviation with ambient traffic ($r_{sp} = .51$, $p = .052$). Objective cognition dissociated with self-rated driving performance ($r_{sp} = -.13$, $p = .652$). After controlling for objective cognition, a significant positive association remained between mental fog and greater speed around ambient traffic ($r_{sp} = .66$, $p = .029$). For lane maintenance, there was no longer an effect of mental fog on left-hand deviation in the drive with ambient traffic (r_{sp} = -.31, p = .289). However, after controlling for objective cognition, mental fog marginally related to less speed variation (r_{sp} = -.60, p = .052).

Sensitivity analyses

Next, we explored other potential covariates for sensitivity analysis. Participant's age, sex, time since injury, and driving experience were unrelated to any driving outcomes ($|rs_{sp}|$ range: .01 to .43, *p*s > .05). Greater post-concussive symptoms, though, corresponded to slower average speed (r_{sp} = -.48, p = .074) and less lane deviation (r_{sp} = -.50, p = .056) during the drive with no ambient traffic. More post-concussive symptoms also related to greater self-reported driving difficulty (r_{sp} = .52, p = .045). Secondly, higher depressive symptoms related to additional lane deviation without ambient traffic (r_{sp} = .54, p = .045). For this reason, we conducted sensitivity analyses controlling for post-concussive symptoms and depressive symptoms.

After controlling for post-concussive symptoms, the impact of mental fog on average speed in the ambient traffic drive remained significant (r_{sp} =.85, p = .001). This also remained significant after controlling for depressive symptoms (r_{sp} = .67, p = .025). Regarding lane maintenance, there was an insignificant effect of mental fog on average lane position after controlling for post-concussive symptoms (r_{sp} = -.45, p = .111) or depressive symptoms (r_{sp} = -.42, p = .133).

Figure 6. Correlation between Mental Fog and *M* Speed with Ambient Traffic.

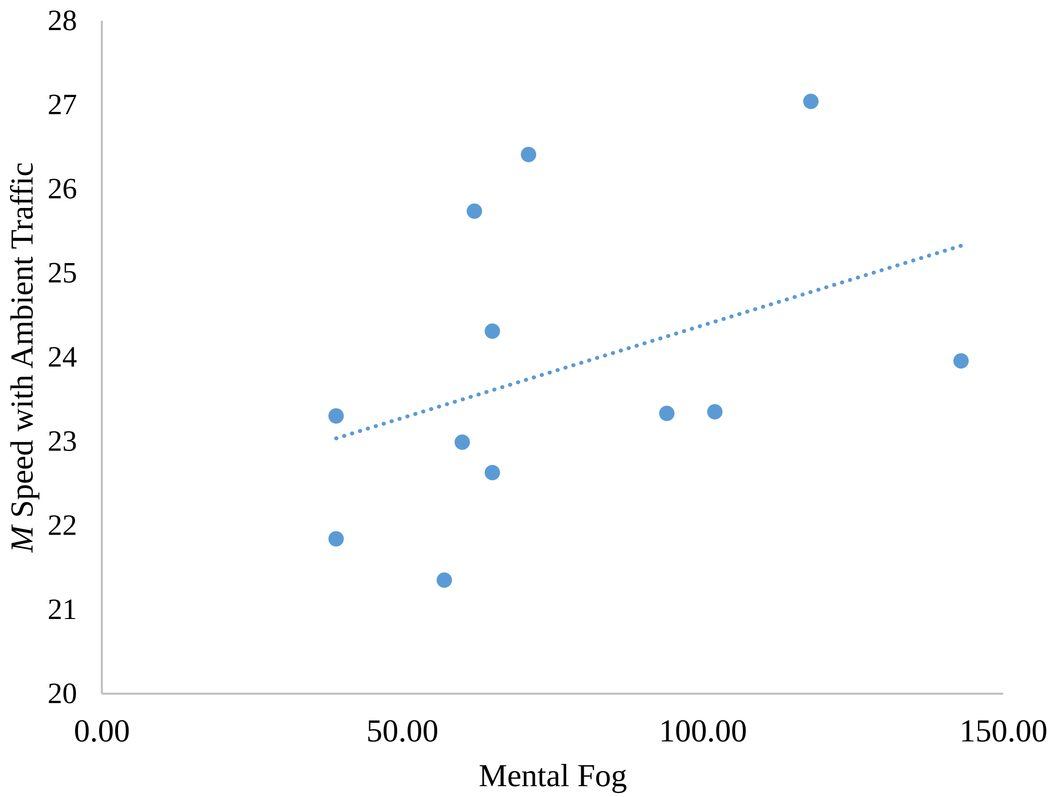


Table 8. Correlations between Mental Fog and Simulated Driving Ability in Moderate-to-severe TBI (n = 15).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. MCS	1.00	-.39	.26	.07	-.03	-.16	-.19	.13	-.09	-.11	-.04	.23	.64*	-.08	-.44†	-.02	.03	.39
2. Obj. Cognition		1.00	-.42	-.12	.24	.02	.09	-.22	-.20	-.32	.37	-.41	-.09	-.74**	.51†	-.27	-.37	-.13
3. POMS-Dep			1.00	.50†	-.39	.29	.24	.02	-.17	.05	.33	-.24	-.03	.48	-.15	-.22	.02	.31
4. PCSS				1.00	-.25	.30	.32	.09	-.48†	-.15	.40	-.50†	-.59†	.23	.02	-.22	-.26	.52*
5. Time Since Injury					1.00	.18	.26	.13	-.05	-.04	.20	.40	.16	-.25	-.07	-.02	-.26	-.16
6. Age						1.00	.97***	.24	-.16	-.39	.16	.09	-.26	.25	-.07	.10	-.32	-.10
7. Driving Experience							1.00	.13	-.15	-.41	.18	.08	-.34	.27	-.09	-.01	-.43	-.12
8. Gender								1.00	-.32	-.35	.09	-.09	-.12	.32	-.22	-.13	.21	.19
9. *M* Speed Drive 1									1.00	.23	-.44	.21	.52†	.15	-.21	.03	.23	-.38
10. *SD* Speed Drive 1										1.00	-.35	.24	.34	.34	.03	.30	.40	-.15
11. *M* Lane Pos. Drive 1											1.00	-.48†	-.25	-.56	.01	-.57*	-.56	.42
12. *SD* Lane Pos. Drive 1												1.00	.29	.20	-.14	.68**	.18	-.37
13. *M* Speed Drive 4													1.00	-.15	-.25	-.03	.25	-.15
14. *SD* Speed Drive 4														1.00	-.48	.06	.49	-.08
15. *M* Lane Pos. Drive 4															1.00	.37	.38	.00
16. SD Lane Pos. Drive 4																1.00	.44	-.26
17. MVCs Drive 4																	1.00	.09
18. BIDSAM																		1.00

Notes. All correlations are Spearman rho. Drive 1 = No ambient traffic scenario; Drive 4 = ambient traffic scenario. BIDSAM = Brain Injury Driving Self-Awareness Measure; MCS = Mental Clutter Scale; Lane Pos. = Lane Position; Obj. Cognition = Objective Cognition composite; PCSS = Post-Concussive Symptom Scale; POMS-Dep = Depression subscale from the Profile of Mood States. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

CHAPTER 6

DISCUSSION

Every year, thousands of drivers in the United States incur a TBI and return to driving within days or years. Like all road users, some drivers with TBI will experience MVCs upon return (Bivona et al., 2012). These events are seldom chance but rather the product of accumulated, modifiable risk factors. In TBI, risk factors may entail a greater number of unsafe driving behaviors compared to controls; these involve greater lane deviations, higher speeds, and slower reactions to hazards (Schmidt et al., 2016). The research literature suggests disrupted cognition can play a role in problematic driving post-injury (e.g., Goodin et al., 2017; Korteling & Kaptein, 1996; Novack et al., 2006; Schmidt et al., 2017); however, the role of self-reported cognition remains enigmatic. Through three aims, the current study examined how mental fog – the metacognitive perception of cognitive problems with clouded thought – related to injury as well as performance on cognitive and driving tasks. Specifically, individuals with mild and moderate-to-severe TBI completed a novel instrument known as the Mental Clutter Scale (Katz et al., 2001) followed by two cognitive evaluation programs (Cogstate® and UFOV®), experimental drives within a high-fidelity simulator, and immediate self-ratings of driving ability (BIDSAM; Gooden et al., 2016).

As predicted under aim 1, individuals with mild TBI reported higher mental fog compared to healthy controls matched on age and gender proportion (*d* = .96). This followed and improved upon the work of Lovell et al.'s (2006) that revealed higher endorsement of "fogginess" on the Post-Concussive Symptom Scale in mild TBI compared to non-injured athletes. First, this study is the first to find a significant difference while adjusting for depressed mood, a factor that inflates subjective ratings of cognitive dysfunction (Chamelian & Feinstein, 2006). Secondly, inspecting mental fog did not rely on a single item but multiple terms describing clouding of consciousness and post-traumatic confusion. Our findings suggest that higher mental fog discerns mild TBI from normal controls on both single-item or comprehensive questionnaires. Furthermore, findings mirror patterns with other subjective cognitive domains: For example, compared to healthy controls, individuals with mild TBI reported significantly higher trouble in memory and attention control, $d = .75$; Dean et al., 2012). At the same time, mental fog improves on prior constructs by combining everyday cognitive failures with perceived cluttered thought – a coalescence that provided larger group distinction. For instance, looking at the Mental Clutter subscales, differences were larger for a lack of mental clarity ($d = 1.04$) than for general cognitive problems ($d = .82$). Together, this group distinction was larger than prior studies asking about cognitive problems alone (Dean et al., 2012). Asking about clouded thought in addition to everyday disruptions in memory and concentration appears optimum for indexing the metacognitive experience of mild TBI that differs from non-injured peers.

Not only was this study one of the few to examine mental fog in mild TBI compared to healthy controls but it was the first to contrast mental fog between mild and moderate-to-severe TBI. Reasoning that mental fog ensues from greater neurological insult, we hypothesized that clouded thinking would be worst for moderate-to-severe injuries. Nonetheless, we recorded similar mental fog between individuals with mild and moderate-to-severe TBI. It is possible that although individuals with moderate-to-severe TBI reported higher mental fog than healthy controls (*d* = 1.25), their head injury dulled offline systems needed to meta-monitor internal cognition and errors. Alternatively, because years passed since injury, varied recoveries in awareness might produce some inconsistency in mental fog self-reports. For example, awareness generally improves over the first year during recovery (Hart, Seignourel, & Sherer, 2009); but after two years, many still portray slightly improved or unamended cognizance (Vanderploeg, Belanger, Dunchnick, & Curtiss, 2007). Self-reported mental fog probably better suits those with intact or recovered awareness able to meta-monitor offline cognition rather than those lacking personal insight. For example, mental fog aligned with actual cognitive performance ($r = -.43$) more so in active drivers with longer time to recover awareness ($M = 4.80$ years, $SD = 3.31$) than nondrivers who had less to recover ($r = -.14$; $M = 2.41$ years, $SD = 2.38$). Regardless, most with moderate-to-severe TBI experienced severe mental fog that related to specific errors in cognition and driving.

Similar subjective dysfunction between mild and moderate-to-severe TBI contradicts prior studies showing that self-reported memory issues increase from mild to severe TBIs (Masson et al., 1996). It also contradicts studies suggesting that cognitive complaints are significantly lower in moderate-to-severe versus mild injuries (Jamora, Young, & Ruff, 2012). As an intermediary position, more research supports higher subjective cognitive impairment in moderate to severe TBI than their peers – even if this does fully approximate the intensity of actual deficits per se. For example, over a quarter of adults with moderate-to-severe TBI report problems with memory (34.1%; Corrigan et al., 2004) slightly higher than rates in community-dwelling older adults (27.1%; Fritsch, McClendon, Wallendal, Hyde, & Larsen, 2014). Moreover, they also report more everyday cognitive failures two to three years post-injury than heathy controls matched on age (*d*s = .62 to 1.40; Hart et al., 20045; Whyte et al., 2006). Recent research also suggests that self-reported executive dysfunction remains more severe in moderate-to-severe TBI than healthy controls (Mangeot, Armstrong, Colvin, Yeates, & Taylor, 2002; Waid-Ebbs, Wen, Heaton, Donovan, & Velozo, 2012). This study supports that general cognitive failures co-occur with problems in cluttered thinking that generate clouded consciousness or mental fog. Future studies should compare moderate-to-severe TBI to healthy controls matched on age; although, little evidence supports a strong age impact on cognitive self-reports without age-anchored comparisons (Buckley, Saling, Ames, & Rowe, 2013; Schultz et al., 2015).

Under aim 2, we explored task-based, cognitive correlates of mental fog. Such an understanding illuminates the errors participants monitor when reflecting on general cognition; it might also signify components of cluttered thinking or in what ways cluttered thinking affects task performance. For mild TBI, mental fog corresponded to slower speed of processing indexed by UFOV®1 but this association was nominal after controlling for depressed mood, contrary to expectation. This implies that although individuals with mild TBI rate higher mental fog than healthy controls, co-occurring depressive symptoms disrupt quantitative cognitive output. This is largely consistent with work showing that psychiatric symptoms account for links between negatively rated cognition and worse task performance after mild TBI – especially after initial recovery (Drag, Spencer, Walker, & Pangilinan, 2012). As explained in other work, this mediation might be driven by slowed information processing from depressive symptoms (McDermott & Ebmeier, 2009), a byproduct of diminished motivation and effort (Silvia, Nusbaum, Eddington, Beaty, & Kwapil, 2014). Indeed, prior studies show that depression slows speed of processing (UFOV®1; Yen, Rebok, Gallo, Jones, & Tennstedt, 2011) which contributes to problems in memory and higher-order problem solving. Thus, slower times might represent reduced motivation rather than interruptions processing quick, appropriate responses. Accumulating evidence does support poor effort as one mechanism for worse task performance in mild TBI across cognitive measures (Lange, Pancholi, Bhagwat, Anderson-Barnes, & French, 2012; Stulemeijer, Andriessen, Brauer, Vos, & Van Der Werf, 2007).

A lack of correlations between depressive symptoms and performance tasks lends minor support for negative mood to explain cognitive issues after mild TBI, however. If depressive symptoms were impactful, then inferior performance would manifest on most speed-based tasks (McDermott & Ebmeier, 2009). Relations to depressive symptoms were not even present among healthy controls, whom negative emotions would aptly explain disrupted cognition absent of pathology. Instead, post-concussive symptoms better explained sluggish cognition after mild TBI. In fact, higher post-concussion symptoms strongly linked to higher self-reported depression and mental fog; this, in turn, connected to worse speed of processing. This aligns with literature underscoring links between post-concussion symptoms and slowed processing speed hours to weeks after injury (Iverson, Lovell, & Collins, 2005) and theorized neuronal mechanisms. Post-concussive symptoms hypothetically gauge neural harm from the kinetic impact undetected from modern imaging techniques (Bigler et al., 2008). Such harm includes white matter hyperintensities and gray matter diffusion anisotropies (Bouix, Pasternak, Rathi, Pelavin, Zafonte, & Shenton, 2013) that disrupt neural transmissions important for quick cognition. While neural harm theoretically coincides with higher depression and mental fog (Dantzer, O'Connor, Freund, Johnson, & Kelley, 2008; Theoharides, Stewart, & Hatziagelaki, 2015), post-concussion symptoms could provide the best self-reported estimate. Regardless of mechanism, post-concussive symptoms might better predict slowed processing speed after mild TBI rather than mental fog or depression.

Additionally, dissociation between mental fog and objective cognition after mild TBI could stem from days allowed for cognitive convalescence. We know that most mental abilities restore within a day or week post-concussion (McCrea et al., 2003); therefore, mental fog might remain via psychological distress or changed self-perception rather than monitoring present cognitive abilities. As mentioned, studies show that residual distress promotes negative views of mentation (Drag, Spencer, Walker, & Pangilinan, 2012). Shown in other populations, feelings of depression can maintain high cognitive complaints for many years in the absence of actual impairment (Hill, Mogle, Bhargava, Bhang, Bell, & Sliwinski, under review; Wang et al., 2015). Likewise, individuals with mild TBI can report depression and cognitive problems up to 6 months after injury (Paniak, Reynolds, Phillips, Toller-Lobe, Melnyk, & Nagy, 2002). As negative views endure long-term, they suggest an integral shift towards negative attributions. For instance, fear and anxiety following mild TBI might create attentional biases that alter self-perception (Broshek, de Marco, & Freeman, 2014); this then engenders subsidiary depression and cognitive complaints. Moreover, youth with mild TBI primarily exhibit lower self-efficacy than before injury and when compared to healthy peers (Gagnon, Swaine, Friedman, & Forget, 2005). Diminished self-efficacy not only factors into who manifests initial mild TBI symptoms (Kroshus, Baugh, Daneshvar, & Viswanath, 2014) but predicts who retains post-concussive symptoms 6 months after injury (Stulemeijer, van der Werf & Vos, 2007). Relevant to this study, low self-efficacy largely explains subjective memory complaints in other populations like older adults (Comijs, Deeg, Twisk, & Jonker, 2002) and stroke (Aben, Ponds, Heijenbrok-Kal, Visser, Busschbach, & Ribbers, 2011). For example, lower confidence predicts more subjective memory concerns even after accounting for anxiety and objective performance (Pearman & Storandt, 2005). Similarly, Rike et al. (2015) found that lower self-efficacy after TBI or stroke linked to greater self-reported problems in executive function. Although scant literature explores self-efficacy and cognitive health after mild TBI, it may play a predominant role in residual perceptions.

Discordance between subjective cognition and performance-based cognition after mild TBI is not unprecedented, though. Spencer, Drag, Walker, & Bieliauskas (2010) indexed perceived problems in general cognition and actual task-based skills in veterans with mild TBI. As strengths, this study excluded individuals with pending compensation incentives and poor effort. Included veterans reported on trouble with concentration, memory, or thinking/organization, later completing a cognitive evaluation of actual ability. Of the remaining sample, 93% reported problems in memory and 92% reported problems in concentration. Like our findings, perceived deficits did not agree with most task performances. The only relation occurred for perceived memory impairment which related to worse long-term memory (r = -.20). Instead, meta-monitored cognitive disruptions moderately related to psychological issues such as depression, anxiety, and post-traumatic stress. We did identify work by Schiehser and colleagues (2011) that linked cognitive complaints and indexed ability. However, Schiehser et al. (2011)'s study varied in that participants with mild TBI meta-monitored problems in executive functions rather than memory before cognitive evaluation. Higher perceived executive dysfunction associated with poorer processing speed, updating, and set-shifting (but no association with memory). Asking about memory and concentration after mild TBI, even cluttered thinking, might not capture isolated cognitive processes after acute mild TBI recovery. Prior literature implicates self-reported failures in goal-oriented behavior as a better subjective domain in this group. Our results indicate that mental fog mostly captures distress and injury severity within mild TBI.

More hypothesized relations occurred within the moderate-to-severe TBI classification. Greater mental fog estimated lower accuracy on Cogstate® tasks indexing reaction time (Detection task), memory (Learning task), and updating (One-Back task). Again, this was mostly true even after accounting for depressive symptoms, a factor that can also deteriorate cognitive performance (McDermott & Ebmeier, 2009). This emulates the work of Johansson et al. (2009) with mental fatigue; greater mental fatigue reflected slower processing speed and less effectual updating of verbal and visuospatial information. Furthermore, perceived memory impairment corresponded to worse learning and updating skills. However, mental fog did not relate to attention as indexed by UFOV® in contrast to other meta-monitored issues. For example, self-reported memory trouble corresponded to worse divided attention (Chamelian & Feinstein, 2006) while self-reported attentional lapses related to worse sustained attention after moderate-to-severe TBI (Robertson et al., 1996). Despite lowered attention after moderate-to-severe TBI, mental fog appears to better capture problems in reaction time, memory, and executive function. In contrast, healthy controls' mental fog related to worse divided attention (UFOV®2) while unrelated in mild TBI. This suggests that meta-monitored mental fog arises from covert disruptions in consciousness and mentation in mild cases but translates into long-term weakened performance in those with more severe, observable brain damage. This aligns with the larger view that cognitive complaints map behavioral disruption when pathology is present but not when absent (Kamkwalala, Hulgan, & Newhouse, 2017).

Lastly, for aim 3, we investigated how perceived mental fog affected simulator-indexed and meta-monitored driving performance. In healthy controls, mental fog disassociated with simulated speed control or lane maintenance. Instead, "thicker" mental fog coupled with higher rated driving difficulty. This relationship, however, became marginal after accounting for sex; therefore, this association likely reflected that individuals reporting mental fog were predominantly female who stated more driving difficulties then men. This aligns with research on the positive illusory sex bias in which males are typically more confident than females when it comes to driving (Tronsmoen, 2008) even though they remain riskier drivers (Monárrez-Espino, Hasselberg, & Laflamme, 2006; Turner, Cathy, & McClure, 2003). For instance, McKenna, Stanier, & Lewis (1991) found that male drivers reported themselves as better than average drivers more so than females; this primary involved exaggerated confidence in lane maintenance (e.g., judging stopping distances, changing traffic lanes, moving onto motorways) and route planning (e.g., navigating unfamiliar areas) rather than speed control. Alternatively, Downing, Chan, Downing, Kwong, & Lam (2010) showed that although sex influences on objective cognition either favors females or the null (Hyde, Fennema, & Lamon, 1990; Hyde, Linn, Marcia, 1988), females tend to perceive themselves as more erroneous on cognitive tasks. This includes perceived defects in attention and executive function (self-regulation and task-management). While mental fog might capture some of these aspects, our self-rated driving instrument directly asked about concentration and regulatory behavior on the road (reacting to roadway signs and ambient traffic) and given immediately after a driving task. Although healthy females did not significantly report higher mental fog than males, perhaps the sex difference arose primarily from online monitoring. For healthy controls, this indicates the importance of adjusting for discrepancies in how sexes report symptoms when inspecting subjective cognition. One such method is to implement norm-based corrections or negative bias checks (Roth & Gioia, 2005); this should be a goal for any clinical subjective measure.

A similar pattern of results appeared for the mild TBI group although unimpacted by sex. One, mental fog did not link with simulator driving indices; and, irrespective of other factors like sex, heightened mental fog corresponded to more self-rated errors in driving. Unique to this group, this relationship mirrored objective cognition: better performances on Cogstate® and UFOV® affiliated with less reported difficulties in the driving simulator. This concurs with prior literature showing that higher cognitive function relates to better driving ratings and more roadway exposure in older adults (Anstey & Smith, 2003). This significant finding in the mild TBI group versus healthy controls likely occurred because injury produced mental fog from acute cognitive disruption rather than symptom intolerance and affect only. As an exploration, there may be a possible mediation: Mental fog was significant even after controlling for objective cognition which might have accounted for some of its total effect. It is possible that mild TBI disrupted cognition and generated depression which elevated mental fog; in turn, dealing with mental fog produced poorer self-rated driving. This would support the idea that metacognition mediates associations between cognition disruption and functional problems (Jackson & Hassard, 2016; Lysaker, Shea, Buck, Dimaggio, Nicolò, Procacci, Salvatore, & Rand, 2010; Ownsworth, & Fleming, 2005). Further research should explore this indirect effect within a larger sample while inspecting the precise cognitive domains mediated.

Prior literature clarifies findings that mental fog and objective cognition negatively contributed to perceived driving ability but not actual driving performance. Many studies in populations with none to minor cognitive issues find that self-rated driving ability does not match with on-road or simulated skills (Marottoli & Richardson, 1998). This might be because worse cognition increases the use of compensatory strategies in those with intact metacognition – thus producing highly heterogeneous, personalized driving patterns. Meng and Siren (2012) found that older adults with cognitive complaints reported worse basic driving skills (e.g., lane maneuvering) but increased use of high-order driving strategies (e.g., decision making). Furthermore, individuals who perceived subjective cognitive decline felt themselves less able to drive and took precautions to improve safety such as avoidance of high risk environments and vision correction (Holland & Rabbitt, 1992). Meta-monitored issues in cognition appear to increase their use of high-order strategies which reduce the number of risky driving habits and situations. This agrees with Nelson and Narens (1990) model that meta-monitored disruption initiates metacognitive control to adapt behavior for goal-related purposes. Thus, for some, greater feelings of mental fog might have increased effort to drive safely in the simulator which led to an unexplained variance in basic driving.

As noted previously, mental fog, likely derived from acute cognitive disruption, might engender psychological internalizations that linger; such changes can influence perceptions of driving errors that do not align with objective simulator outcomes. For example, correlation between mental fog and poorer self-rated driving could partially reflect diminished self-efficacy. After a mild TBI, adolescents or young adults might feel less confident in their protection or ability to perform, especially if the injury involved a self-initiated task like sports (Gagnon, Swaine, Friedman, & Forget, 2005). Youth might internalize and generalize these feelings into fears about keeping oneself safe on the roadway and/or skillfully operating a vehicle as well. This would especially occur among those who incurred mild TBI from MVCs, the leading cause of such injuries (CDC, 2017). Prior research supports attenuated self-efficacy among individuals with perceived driving problems or with head injury: Over and above objective cognition, Ackerman, Vance, Wadley, & Ball (2010) found that low self-efficacy contributed to perceived poorer self-rated ability and subsequent cessation over five years in older adults. Secondly, higher self-efficacy related to better self- and instructor-rated performance in novice drivers (Victoir, Eertmans, van den Bergh, van den Broucke, 2005). Furthermore, survivors of stroke felt lower driving self-efficacy than healthy controls which entailed weak confidence in handle high risk situations (e.g., heavy traffic), react to cues (e.g., traffic signals), and complete difficult maneuvers (e.g., turning right across oncoming traffic; George, Clark, & Crotty, 2007). Thus, feelings of poor driving ability might denote weakened self-efficacy produced from beliefs that one's cognition is incapacitated and unclear.

Feelings of poor driving self-efficacy might be advantageous for patients and clinicians alike. Early on, deficits in attention and information processing might be monitored (i.e., mental fog) and compromise confidence in safe driving. In the absence of clinical recommendations, this leads to self-regulation after injury that limits roadway exposure and high-risk situations and maneuvers. In addition, lower self-efficacy might enable drivers to engage compensatory strategies when they do drive and attempt risky situations. In a brain injury sample, Rike et al. (2015) found that low self-efficacy decreased daily mileage driven and increased compensatory strategies; in addition to avoidance, compensatory behavior involved driving slower speeds, with others, or when feeling well. Moreover, less self-efficacious individuals reported fewer driver mistakes and inattention which indirectly related to fewer minor collisions. Such trends may account for our insignificant correlations between mental fog with simulator outcomes. Persons reporting more driving difficulties were more self-efficacious; such persons implemented greater effort and compensation during driving simulation. Thus, low self-efficacy or self-rated driving ability might reflect actual driving abilities to the extent that behavioral compensation is considered.

Dampened self-efficacy after injury provides an opportune intervention window as well. In particular, trainers can help injured youth gain mastery experiences on the roadway that improve self-efficacy in normal and risky situations; this can pair with methods used for return to sports (Chase, Magyar, & Drake, 2005). One method is error-based training in which youth undergo on-road or simulated driving with instructor feedback; drivers are then allowed reattempts following by other modules with varied environmental and task demands (Ivancic & Hesketh, 2000). Error-based training is important as many young drivers exhibit high driving self-efficacy without performance awareness that leads to disastrous roadway incidents. Generally, high self-efficacy primes drivers to commit riskier behaviors such as excessive speeding, intoxication, or distraction (Hill, Styer, Fram, Merchant, & Eastman, 2014; Morisset, Terrade, & Somat, 2010) and inflates the odds of crashes and violations (Wells-Parker, Williams, Dill, & Kenne, 1998). Training provides an opportunity to corroborate feelings of self-efficacy with mastery (proven skill) and applied knowledge (comprehension of safety behaviors); this can entail a reduction of unfounded sureness and an increased confidence in trained skill. Fortunately, individuals perceive more realistic self-efficacy with greater driving experience (Delhomme & Meyer, 2004) as shown in by the positive correlation between driving experience and self-rated driving errors in the mild TBI group.

In the moderate-to-severe TBI group, we found a contrasting pattern of relations between mental fog and driving. Foremost, mental fog was unrelated with self-ratings of driving unlike in the mild TBI group. This aligns with depleted awareness after moderate-to-severe TBI not common in minor head injuries. Secondly, it could reflect strong desire to resume driving, even though we informed participants that simulator performance was confidential and used for research purposes only. Therefore, while they felt higher cognitive problems, they might have perceived disincentives to reporting driving issues. In fact, when compared to mild injury, persons with moderate-to-severe TBI reported significantly lower driving difficulty but at a degree comparable to controls. These results differ from prior studies demonstrating similar driving confidence in persons with stroke compared to controls (McNamara, Ratcliffe, & George, 2014) but align with reports proceeding an actual driving task. After a simulated drive, stroke survivors overestimated performance compared to controls (McKay, Rapport, Bryer, & Casey, 2015). If this reflects poor self-awareness rather than social desirability, then a major challenge belies roadway safety: Higher confidence leads to less self-regulated behavior in people who commit riskier driving (i.e., avoidance; McNamara, Walker, Ratcliffe, & George, 2015). This could also make driving rehabilitation harder as participants with high confidence are less inclined to adopt safer driving techniques. Altogether, worse trainability and unused compensation might explain higher crash risk for those returning behind the wheel after TBI. Thus, knowledge of general cognitive problems (offline monitoring) without abilities to monitor applied task performance (online monitoring) becomes a challenge for reducing injury risk.

In addition, mental fog anticipated issues in objectively measured driving behavior. Overall, individuals with higher mental fog in the moderate-to-severe TBI group drove faster and tended to deviate from the centerline more than others. More importantly, this did not occur in the basic car operation drive but when navigating a visually complex environment with ambient traffic and billboards. Findings that low-demand environments provide unrealistic speed outcomes could explain this discrepancy (Bella et al., 2008). It’s more likely, however, that drivers with higher mental fog failed to incorporate information on ambient traffic behaviors and speed limit signs to produce safer, slower driving. Alternatively, the cognitive demands produced by a busy, novel environment pulled on cognitive domains harmed by mental fog. For example, research shows that safe driving depends on quick processing speed and intact updating skills

(Anstey et al., 2005), weakened by mental fog. Findings emulate work in other constructs such as mind wandering. Yanko and Spalek (2014) found that participants who mind-wandered during simulation sped faster than non-wandering participants; they also exhibit slowed reaction times and shorter headway distance, variables not examined in our study but alluding to poor hazard perception and lane positioning. Furthermore, Kass et al (2010) found that boredom proneness within TBI corresponded to higher speeds and higher centerline crossings. Mind-wandering and mental fog conceptually overlap as both represent inefficient executive control or task-monitoring (Mittner, Boekel, Tucker, Turner, Heathcote, & Forstmann, 2014). Mind wandering, however, occurs predominately in situations with low task demands and absent traffic whereas mental fog impacted driving in a situation with higher cognitive-perceptual load and traffic. Thus, mental fog might represent inefficient task monitoring when driving complex and novel situations; whereas mind wandering, common after moderate-to-severe TBI (boredom, Goldberg & Danckert, 2013) explains risky driving in familiar, low demand routes.

Limitations

This study was not without limitations. First, although the mild TBI group matched healthy controls on age, this was not so for the moderate-to-severe TBI cases regarding age. Because parent studies held discrepant goals, the moderate-to-severe TBI group was much older than other groups. Cognitive differences might subsequently stem from slowed processing speed, a cognitive domain highly susceptible to age-normative decline (Salthouse, 2000). Contrary to such expectations, individuals with moderate-to-severe TBI did not show worse speed of processing (UFOV®1) or reaction times

(Cogstate® Detection and Identification tasks) – counterintuitive of an age effect. Instead, discrepancies emerged for high-order domains: the moderate-to-severe TBI group showed worse divided attention, selective attention, and working memory compared to the mild TBI and healthy groups. Executive dysfunction appears indicative of neurological pathology rather than general aging (Collette, van der Linden, & Salmon, 1999; Jurado & Rosselli, 2007). Severity of brain injury, therefore, is a better explanation for problems in these domains rather than being slightly older. Moreover, although persons with moderate-to-severe TBI reported higher mental fog than the uninjured group, it's unlikely that younger age fully explained this incongruity. Most studies show no age differences in self-reported cognition between young to middle aged individuals (Papaliagkas, Papantoniou, Tsolaki, & Moraitou, 2017). As poorer working memory corresponded to greater mental fog, it's likely that higher mental fog emanated from disrupted executive functions attributed to moderate-to-severe TBI.

Secondly, inclusion criteria for mild TBI required symptomatic individuals (we included individuals > 13 on the PCSS) versus less symptomatic concussions. High symptoms can bias self-reports (Lange & Iverson, 2010) and possibly explain higher mental fog in mild TBI versus uninjured controls. Researchers criticize that studies on mild TBI recruit the worst, negatively biased cases (McCullagh & Feinstein, 2003). Our results counter this notion as the mild TBI group exhibited similar depressive symptoms as healthy controls. Moreover, post-concussive symptoms do not solely represent a negativity bias but implicate individuals with disrupted neuropsychological performance and neurological abnormalities (Leininger, Gramling, Farrell, Kreutzer, & Peck, 1990; Taylor et al., 2010). Our protocol also required individuals to report lost consciousness, memory disruption, or problems balance alongside post-concussive symptoms; this prevented inclusion of highly symptomatic persons without primary indicators of concussion. Furthermore, our inclusion of mild TBI aligned with guidelines from national and international agencies (American College of Rehabilitation Sciences, 1993; Borg, Holm, Cassidy, Peloso, Carroll, Von Holst, & Ericson, 2004) and recruitment protocols from prior research (Eisenberg, Meehan, & Mannix, 2014). Stringent criteria help to identify clinically significant cases that warrant medical attention as denoted by prior literature. Leininger and colleagues (1990) found that individuals with mild TBI displayed worse cognition than healthy controls or low symptomatic concussion. Moreover, cognitive complaints predominately derived from personality and affective factors in healthy controls or low symptomatic concussions rather than neuropsychological deficits; meanwhile, acute cognitive disruption contributed to subjective complaints in mild TBI (Clarke, Genat, & Anderson, 2012). Moreover, mild TBI cases show weaker cognitive performance compared to asymptomatic concussions (Fazio, Lovell, Pardini, & Collins, 2007). Thus, those with high symptomatic concussions or mild TBI represent a clinically relevant group for inspection versus low symptomatic cases. Nonetheless, minimally symptomatic concussions might show problematic driving that warrants assessment as well (Classen et al., 2011).

Third, our study recruited healthy controls instead of medical controls. Many argue that researchers should compare mild TBIs to non-head injuries rather than unharmed peers. This rationale seems cogent as individuals with non-head injuries develop symptomology and distress like mild TBI (Brewer, Petitpas, van Raalte, Sklar, & Ditmar, 1995; Leedy, Lambert, & Ogles, 1994; Levi & Drotar, 1999). Thus, differences might arise from generic injury effects caused by patienthood and premorbid factors (personality and emotional regulation) rather than unique harm from mild TBI (Binder, 1997). A common medical control group involves general trauma patients without head injury (Ponsford, Cameron, Fitzgerald, Grant, & Mikocka-Walus, 2011) while others collect orthopedic injuries specifically (Sheedy, Geffen, Donnelly, & Faux, 2006). Regardless of medical control group, few data support a common injury effect. When seen at the emergency department visit, persons with mild TBI demonstrate weaker balance and cognitive performance than orthopedic controls (Sheedy et al., 2006). Moreover, individuals with mild TBI report higher severity and frequency of post-concussion symptoms than trauma controls one week to one month later (Paniak, Reynolds, Phillips, Toller-Lobe, Melnyk, & Nagy, 2002). In fact, not until many weeks later do groups reach similarity: Compared to non-head injuries, individuals with mild TBI exhibited similar symptoms and neuropsychological performance one-month post-injury (Babikian, Satz, Zaucha, & Light, 2011). Paniak et al. (2002) also found similar symptoms three months post-injury between mild TBI and trauma controls. Nonetheless, some mild TBIs demonstrate higher post-concussive symptoms compared to orthopedic injury (d = .20) or uninjured groups several months later (d = .19; Ettenhofer & Barry, 2012). Thus, justification for using medical controls group might not be applicable until months after recovery. Even then, Mathias, Dennington, & Bigler's (2013)'s found that healthy and orthopedic controls were alike on current psychosocial and cognitive function as well as premorbid psychiatric and medical history.

Lastly, demographic stipulations limit the generalizability of our findings. Regarding race, over 70% of our sample was white. Research suggests that non-white individuals receive less medical attention after TBI compared to white counterparts, even after controlling for healthcare coverage (Meagher et al., 2015). Also, negative outcomes can be more pronounced for black individuals after TBI compared to whites even after controlling for socioeconomic status (Yeates et al., 2002). Future research should acknowledge possible health disparities that promote unresolved problems with mental fog or other subjective symptoms long term. Secondly, injury mechanisms included sport-related activities within the mild TBI group and MVCs or falls within the moderate-to-severe TBI group; results, therefore, may not generalize to combat- or blast-related TBIs. Specifically, post-traumatic stress occurs with combat-associated TBIs that ambiguates, intensifies, and maintains post-injury symptoms (Belanger, Kretzmer, Vanderploeg, & French, 2009). This might even explain why individuals with military TBIs have double the crash risk than other TBI groups (Carlson et al., 2016; Formisano et al., 2005). Furthermore, combat TBIs receive care with better quality and outcomes than most civilians (DuBose et al., 2011). Therefore, combat-associated TBIs provide a future opportunity to explore subjective cognition and driving within a high-risk, well-monitored group. Our sample might still be generalizable as some studies show that combat TBIs are indistinguishable from mild TBI on post-concussion symptoms, psychological health, or cognitive performance (Luethcke, Bryan, Morrow, & Isler (2011).

Our measures also revealed some limitations. First, driving simulation was simplistic, involving a freeway drive with no navigational goal or dual-task demands. Michaels et al. (2017) note that driving scenarios should be moderately demanding to sensitively detect aberrant driving behavior. Certainly, if mental fog was decisive for safe driving, it would likely matter most for high-load, complex situations. In fact, this might explain why mental fog corresponded to faster speeds and somewhat deviant lane positioning in the ambient traffic condition but not the non-ambient traffic drive in the moderate-to-severe TBI study. Not only did participants drive with other cars on the road but participants observed billboard messages simultaneously. Moreover, it might explain why mental fog was not related to simulated driving after mild TBI as participants were not committing many naturalistic, cognitively-demanding behaviors such as distraction or divided attention.

Another limitation was that mental fog was inexorably subjective. Many view subjective measures as unsubstantiated, regarding them as poorly reliable and invalid. However, cognitive self-reports demonstrate acceptable to high external reliability when paired with informant and clinician reports (Roth et al., 2013; Ventura, Cienfuegos, Boxer, & Bilder, 2008); thus, an informant scale grounded on observable behaviors might corroborate patient-rated mental fog. Concerning construct validity, mental fog showed divergent validity as it was not multicollinear with mood or post-concussive symptoms; moreover, mental fog showed convergent validity through relations to weakened processing speed and working memory after moderate-to-severe TBI. Secondly, many argue that subjective measures have questionable clinical value. On the contrary, subjective cognition strongly predicts important TBI-relevant outcomes like cognitive decline, neurological pathology, and mortality (Hohman, Beason-Held, Lamar, & Resnick, 2011; de Groot., de Leeuw, Oudkerk, Hofman, Jolles, & Breteler, 2001; St. John & Montgomery, 2002; Visser et al., 2009). Our study implicates that mental fog might predict injury risk via confidence to return to drive and speeds among high-demand roadways. Lastly, as seen in other injury symptoms like pain, the internal human experience will remain partially subjective despite massive efforts for objectivity (Robinson, Staud, & Price, 2013). Self-report is not mental fog's coupe de grace but the only source for illustration – though corroboration with objective measures provides some clarification as attempted in aim 2. Subjectivity also provides an individual ownership of their cognition and agency to interpret struggles without assuming they interact mechanistically or passively with the world (Graham & Stephens, 1994). Acknowledging patient narratives can also improve their sense of autonomy and trust with the clinician (Greenfield, Ignatowicz, Belsi, Pappas, Car, Majeed, & Harris, 2014).

Lastly, depressive symptoms were self-reported instead of obtained from a structural clinical interview. Structured interviews align closely with diagnostic criteria while ruling out concomitant psychopathology. Fortunately, the POMS depression subscale retains high criterion validity with structural interviews to capture clinician-rated depressive symptoms. For example, Patterson, Young, Woods, Vigil, Grant, & Atkinson (2006) found that the POMS correctly classifies persons with major depressive disorder with 80% accuracy. Another study found a classification accuracy of 92% (Wilkins, Hamby, Robertson, Knorr, Barry, & Hall, 1995). The POMS also appeared appropriate for our samples due to high reliability and construct validity in mild and moderate TBI samples (Bay, Hagerty, & Williams, 2007). Furthermore, POMS is the primarily mood instrument used in athletic samples from which many mild TBIs will derive (Terry & Lane, 2000).

Strengths

Aside from limitations, this project exemplified many strengths. First, we included a broad variety of individuals with TBI but kept mild and moderate-to-severe cases separated for comparison. Although TBI is spectral (Decuypere & Klimo, 2012), analyzing mixed samples, done in many studies (e.g., Chamelian, Laury, & Feinstein, 2006) can hurt generalizability. As shown in this project, there were discrepant associations between mental fog with cognition and driving between groups; this supports that combining these samples would have been inappropriate (regardless of age differences). Next, individuals participated within a key return to drive period. Individuals with mild TBI entered the study within two weeks post-injury by which 90% will return to drive (Bottari et al., 2012). Whereas, moderate to severe TBI partook within three years post-injury in which decisions to return to drive are still occurring (Novack et al., 2010). For the moderate-to-severe group, purposive recruitment not only sampled active drivers but also those who sought to return to drive and could not either due to clinician decision (obvious impairments) or family instruction (cleared to drive by clinician but not yet allowed by caregivers). Thus, the impact of mental fog on driving was captured at a time in which those able quickly return to the road do so while many remain on the cusp allowing for better recuperation. During this return to drive period, clinicians will likely witness driving behaviors (e.g., avoidance) not attributed solely to cognitive deficits but persistent symptoms and internalizations like mental fog or diminished self-efficacy.

Also, individuals matched on several influential factors. First, groups matched on gender and race proportions. These factors are pertinent to analyzing driving behavior as males commit greater driving violations and retain higher crash risk than females (Massie, Campbell, & Williams, 1995; Rhodes & Pivik, 2011). Regarding race, black men have the highest crash risk compared to other racial backgrounds (Braver, 2003); thus, a higher composition might confound group differences. Lastly, participants matched on prior crashes and tickets in the last three years. Some studies show that individuals with TBI incur more pre-injury driving violations and crashes than peers (Schanke, Rike, Psychol, Molmen, Psychol, & Olsten, 2008) which might confound post-injury driving behavior. Individuals with TBI might have been riskier drivers before injury that makes them appear riskier afterwards. Fortunately, our study aligned with others shows no pre-morbid differences in TBI and non-TBI drivers (Pietrapiana et al., 2005).

Moreover, we implemented strong measures. First, we measured subjective cognition using a novel but validated instrument, the Mental Clutter Scale, which captures a full arrangement of problems in memory, attention, and thinking but uniquely captured a lack of mental clarity. Prior literature within and outside of TBI rarely implements detailed questionnaires on internal perceptions of cognitions; instead, one item questions typically screen individuals for subjective difficulties. While one-item measures can capture the “snapshot” of a construct (Bowling, 2005), they have poor predictive value and capture limited variation (Diamantopoulos, Sarstedt, Fuchs, Wilczynski, & Kaiser, 2012). As seen in prior work, asking about problems in “memory” or “attention” can detect group differences (Hart et al., 2005) but their ability to predict behavioral outcomes in TBI have been limited aside from affective symptoms (Stulemeijer et al., 2007). For example, dichotomizing individuals by cognitive problems

(“Yes” or “No”) was unpredictive of return to driving (Hawley et al., 2001). Employing instruments with wide continuous scales might enhanced clinical efficacy. For instance, the Behavioral Rating Inventory of Executive Function (BRIEF), a detailed scale of self-reported executive function, associates with several driving behaviors after TBI, in part, due to its robust psychometrics. The BRIEF provides multiple scales that permit substantial variation while showing inter-item consistency. Likewise, Mental Clutter Scale was able to capture a wide variation in mental fog that showed high inter-item reliability and successfully predicted driving outcomes.

Second, this study was one of the first to examine self-reported cognitive issues and simulated driving. Prior studies on subjective cognition and driving focused on self-reported outcomes like day-to-day driving violations and errors (Driving Behavior Questionnaire; Allahyari et al., 2015; Wickens, Toplak, & Wiesenthal, 2008). In other studies, they also focus on self-reported times pulled over, number of received tickets, and MVCs (Larson & Adlerton, 1997; Pope et al., 2016). These studies link meta-monitored cognitive errors to problematic driving via self-report; but inspecting ties to simulated driving might provide an objective link. As the first other study, Kass et al. (2010) linked self-rated cognitive failures to greater deviation in lane position, slower reaction times, and attentional lapses on the roadway. In contrast, our subjective cognitive domain of mental fog linked to self-rated driving errors but not to simulated driving metrics in persons with mild or no TBI. Only in persons with moderate-to-severe TBI did internally perceived cognitive problems relate poor objective performance (i.e., driving speed. This leaves further opportunities to explore how different cognitive self-reports predict higher crash risk and errors and why. For instance, internal cognitive issues might diminish concentration and cognitive control during complex or distracted driving rather than basic ability. Furthermore, relations might differ across road user attributes and medical conditions – suggested from our discrepant findings between mild and moderate-to-severe TBI. This opens avenues to consider this topic within other cognitively-impacted groups at high crash risk.

Moreover, even though this study assessed subjective ratings of driving ability, our instrument showed strengths. Foremost, the BIDSAM did not ask participants to rate abilities in comparison to peers, a method that produces extreme bias towards overconfident ratings (Sundström, 2008). Specifically, comparison measures of self-rated driving ask participants to mark themselves anywhere from below average to above average drivers compared to others. On such measures, almost all will report themselves as average or above average, thus, ineffectually capturing wide or accurate ranges of subjective ability. Another issue with subjective driving ratings besides peer-comparison are their dependence on offline meta-monitoring. Most scales ask participants to decouple and reflect on driving abilities within an extended time frame (a few weeks to a year). Along with concerns that such ratings are highly susceptible to negative recall bias and affect, there is another concern regarding their dependency on long-term memory, substantially harmed after a TBI (Reid & Kelly, 1993). Plus, concerning metacognition, individuals with TBI positively rate performance despite high inaccuracy (O'Brien & Kenney, 2016); therefore, they might provide erroneous judgements on driving ability. To account for this, the BIDSAM asks participants to rate abilities immediately after a task, thus utilizing more accurate online meta-monitoring (Chiou et al., 2011). While these did not relate to computer calculated speed control or lane positioning per se, ratings approximate clinician and on-road ratings, albeit to a lesser degree (Gooden et al., 2017).

Lastly, our study captured objective cognition via computerized batteries established to be feasible and clinically relevant. Our primary instrument that also showed the highest impact was the Cogstate Brief Battery® completed within 10 minutes. Prior studies predominantly inspected group differences on Cogstate® before and after intoxicated driving (Charlton & Starkey, 2015; Starkey & Charlton, 2014), whereas this study examined typical driving ability. We found that Cogstate® related to self-rated simulator driving in the mild TBI and simulated speed and lane positioning the moderate-to-severe TBI; thus, Cogstate® might be a useful for decisions on driving fitness after TBI. Many offices already use this instrument for this reason after mild TBI, providing higher rates of driving clearance for patients with higher Cogstate® scores (MacDonald, Patel, Young, & Stuart, 2017). However, this battery appears clinically pertinent for moderate-to-severe TBI as it correlates with standard neuropsychological tests (Overton et al., 2011) and sensitively detects impairment (Maruff, Thomas, Cysique, Collie, Snyder, & Pietrzak, 2009) – even among those without awareness (Lim et al., 2012). It even mimics batteries already used for decisions on driving fitness after moderate-to-severe TBI (Duquette et al., 2010).

In addition, participants completed UFOV®, a task relevant to risky driving and finished within 15 minutes. Although unrelated to performance within our focused driving simulation, this instrument remains ecological valid to detect at risk drivers. Owsley et al. (1998) found that older drivers with impaired UFOV® scores were twice more likely to incur a MVC over five years; and higher risk mostly derived from problems in divided attention (Classen, Levy, McCarthy, Mann, Lanford, & Waid-Ebbs, 2009). Prior meta-analyses confirmed this eight studies and thousands of participants (Ball, Wadley, Edwards, Ball, & Boenker, 2001; Clay, Wadley, Edwards, Roth, Roenker, & Ball, 2005). Greater impairment is also seen in groups with high crash risk such as multiple sclerosis (Schultheis, Garay, & DeLuca, 2001) and Alzheimer's disease (Rizzo, Anderson, Dawson, Myers, & Ball, 2000). Moreover, UFOV® predicts passing on-road evaluations and driving errors with high specificity and sensitivity (Classen et al., 2009; Duchek, Hunt, Ball, Buckles, & Morris, 1998). Beyond dichotomizing fitness, individuals with moderate-to-severe TBI who demonstrate worse UFOV® scores receive lower driving ratings by certified evaluators (Schneider, Novack, Alderson & Bush, 2000).

Future directions for mild TBI

The *Road to Zero* traffic fatalities (National Safety Council, 2016) will require attention towards TBIs and driver safety. But, although mild cases comprise 80% of TBIs and associate with risky driving, scarce guidelines exist on how to monitor driver fitness after a hit. Recent reviews recommend that physicians request that patients wait 24 hours or more before returning to drive (D'Apolito, Mazaux, Le Guiet, Rossignol, Busnel & Lemoine, 2015) although supported by little evidence (Baker et al. 2015). Such a recommendation may yet be hazardous: while quick cognitive recovery occurs, debilitated cognition can persist weeks later and disturb driving (Classen et al., 2011). Certainty, best fitness evaluations derive from on-road assessment (Fox, Bowden, & Smith, 1998) – but this golden approach presents obvious drawbacks for mild TBI. Roadway evaluations are expensive (mostly uncovered by insurance), time-consuming, and insensitive to subtle complications, i.e., it is unlikely that someone with mild TBI would overtly fail on-road assessment. Plus, by the time evaluation occurs, clinicians have missed the riskiest window to determine return to drive. Another solution might be to implement routine cognitive assessment with tools like Cogstate®; however, cognitive examinations lose initial value as persons with mild TBI perform indistinguishably from peers shortly post-injury. This could arguably due to either true recovery or successful implementation of compensatory strategies. Furthermore, UFOV® and other well-validated tasks poorly account for slow hazard perception (Preece, Horswill, & Geffen, 2010) and long-term crash risk after mild TBI (Schneider & Gouvier, 2010). Thus, persistent psychological factors might heighted crash risk after mild TBI.

Implications for mild TBI

Signified from this study, mental fog stands as a pertinent psychological factor for safe driving after mild TBI. Mental fog might manifest from early cognitive deficits and persist via ongoing distress and altered self-perception. Despite not corresponding to current cognitive function, mental fog showed two strengths with significant clinical implications. First, mental fog strongly explained self-rated difficulties in simulated driving even a week post-injury. Secondly, mental fog accounted for self-rated driving ability over and above quantified cognition. Because self-ratings closely align with informant and clinical evaluations after mild TBI (Leathem, Murphy, & Flett, 2010), this implies that meta-monitored mental fog captures observable driving errors. Mental fog assessment might, therefore, inform clinicians on driver aptitude and confidence when making return to drive decisions – especially when objective tests provide few clues. Clinicians already assess fogginess on the Post-Concussion Symptom Scale; but this study advocates that clinicians acknowledge this symptom as unique and relevant to function limitations. Indeed, various post-concussive symptoms might inimitably predict different functional limitations such as fogginess and driver ratings. Future studies should include ratings from professional driving evaluators to confirm the association between mental fog and observed driving skill. Other than the BIDSAM, validated scales could include the Driving Assessment Scale and Global Rating Scale (Novack et al., 2009).

Future directions for moderate-to-severe TBI

For moderate to severe TBI, ideal decisions on driving fitness derive from three processes: comprehensive cognitive testing regarding domains of attention, visual scanning, memory, and executive function; on-road driving assessment within varied environments; and informed decisions considering medical history and informant reports (D'Apolito et al., 2015). Although on-road assessment remains the golden standard for determine driver-fitness, it is not always possible. Mainly, while some insurances pay for on-road evaluations after moderate-to-severe TBI, most will not cover use the full cost; thus, many families cannot afford this option. In this case, driving fitness decisions rely on subsidiary cognitive batteries and medical data prior to mandating on-road evaluations, i.e., off-road evaluation. Though not tested here, mental fog might assist initial evaluations as individuals with deficient cognition, but low mental fog, might clearly be unable to drive safely. As an area for future research, such persons likely would be unmindful of driving errors and unable to relearn safe or compensatory behaviors. But this discrepancy also presents a novel treatment avenue: to bridge the metacognitive gap between perception and indexed ability.

Methods to improve basic metacognition have received much attention (Hertzog & Dunlosky, 2011; Mortiz, Andreou, Schneider, Wittekind, Menon, Balzan, & Woodward, 2014) but newly studied in TBI. Programmic features entail error feedback, otherwise known as "sowing the seeds of doubt" (Mortiz et al., 2014). Secondly, they teach compensatory skills such as better memory strategies (Carretti, Borella, de Beni, 2007) or self-testing (Bailey, Dunlosky, & Hertzog, 2010). For example, Rigon and colleagues (2017) randomized individuals with severe TBI to either a multiweek group therapy for self-awareness training or educational training. Self-awareness training exercised metacognition through skits where participants observed an actor's performance and then rated their own on various activities. A psychologist evaluated self-ratings to provide realistic feedback. Over and above general group therapy effects, teaching self-awareness led to improved metacognition and objective cognition. An early meta-analysis (Schmidt, Lannin, Fleming, & Ownsworth, 2011) supports these results, finding a large robust effect between error feedback and improved metacognition (Hedges g = .64). Utilizing similar techniques, clinicians might be able to help participants approach standard metacognition; this could prepare one to rehabilitate driving skills and compensate for ongoing deficits. One issue, however, is that training paradigms can have limited transfer to other performance domains (Zelinski, 2009). Even in our study, although participants with moderate-to-severe TBI could monitor cognitive issues, they could not accurately monitor driving errors (unlike the mild TBI group). Once subjective evaluations like mental fog approximate actual performance, metacognitive training should transfer skills to driving performance.

As general metacognition recovers, clinicians might apply training protocols to driving-specific tasks. Creating more realistic perceptions would allow risky drivers to employ compensation and self-regulation to advance theirs and others' safety (Rapport, Bryer, & Hanks, 2008). No program yet applies metacognitive training to driving rehabilitation after TBI, but programs show efficacy in other at-risk groups like teens and older adults (Lavalliere, Simoneau, Tremblay, Laurendeau, & Teasdale, 2012; Senserrick & Swinburne, 2001). Effective methods provide realtime error feedback through in-vehicle technology (Toledo, Musicant, & Lotan, 2008) or programmed simulation (Ivancic & Hesketh, 2000); best methods incorporate feedback with informants to improve driver's error awareness as well (Farah et al., 2014). More importantly, training gains derive directly from improved metacognition than practice alone (Keith & Freses, 2005). Similar programs might rehabilitate driving after moderate to severe TBI but require validation and randomized-control designs. Such programs would benefit from high-fidelity driving simulators and newly developed driving safety apps.

Implications for moderate-to-severe TBI

Lastly, even though driving fitness and rehabilitation programs unquestionably prevent needless crashes, returned drivers with TBI retain higher crash risk long-term. On-road assessments have high specificity to identify unfit drivers but low sensitivity to predict crash-risk for permitted drivers. Indeed, if on-road assessments were highly sensitive, then MVCs would not remain a top killer in the United States (CDC, 2016). A tempting logic purports that overt risky driving must precede extreme consequences like crashes. Nevertheless, most crashes likely derive from subtle erroneous tendencies within those who can operate a vehicle well for an evaluator. For this reason, clinicians and caregivers should continuously assess risk among those “fit” to drive. As shown here, mental fog might help identify persons with ongoing troubles in cognition, metacognition, and driving regulation. Clinicians might even decide to follow up reports of high mental fog with further neuropsycholgocial evaluation. For persons with intact or recovered awareness, high mental fog with cognitive disruption might inform the clinician that the person employs extra attention and strategy (compensatory strategies) to operate a car safely that could fail in high intensity or distracted situations. Providing information on how to minimize distraction or high-risk situations might empower driver safety in this subgroup. For those with moderate mental fog but high cognitive deficits, graduated restrictions might improve safety until they achieve adequate error awareness, imposed by trust between clinician, client, and caregivers. This could include circumventing high traffic situations, non-caregiver passengers, or night time driving. Moderate mental fog without observed deficits might still be worthwhile to examine as subjective cognition can predict crashes and tickets over and above objective decrement (Pope et al., 2016); this is likely because self-report cognition captures ecologically-valid, self-regulatory failures unindexed by isolated cognitive tests (Toplak, West, & Stanovich, 2013). Overall, recognizing metacognitive experiences related to faulty decisions, sluggish reactions, and faster driving might allow individuals and their healthcare providers reduce future injury risk.

CONCLUSION

TBI survivors who return to driving are potentially at higher risk of MVCs, possibly due to ongoing difficulties with driving. One valuable area to inform safety risk is cognitive difficulties either measured objectively or through self-report. Prior to this study, no research examined the role of subjective cognition to predict simulated driving after TBI. This study showed that mental fog, meta-monitored cognitive problems with a lack of mental clarity, remains higher in TBI compared to controls and corresponds to problems in objective cognition and simulated driving performance. Better understanding of self-reported cognitive difficulty may help better identify individuals in need of further evaluation, rehabilitation, or delayed return to drive. Future work should explore the unique predictive value subjective cognition on driver rehabilitation outcomes, fitness status, and prospective crash risk.

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APPENDIX

IRB APPROVAL

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

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701 20th Street South
Birmingham, AL 35294-0104
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APPROVAL LETTER

TO: Bell, Tyler R

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

DATE: 16-Feb-2018

RE: IRB-300000705
Driving Through the Fog: Traumatic Brain Injury and Mental Clutter on Driving

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The IRB reviewed and approved the Initial Application submitted on 15-Feb-2018 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: Expedited (Category 5)
Determination: Approved
Approval Date: 16-Feb-2018
Approval Period: One Year
Expiration Date: 15-Feb-2019

The following populations are approved for inclusion in this project:

- Children – CRL 1

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

- Waiver of Informed Consent
- Waiver of HIPAA

Documents Included in Review:

- hsp.180215.clean
- consentwaiverauth.180214.clean
- datacollection.180214