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CRITICAL REVIEW

A Systematic Review and Meta-Analysis on the Association Between Driving Ability and Neuropsychological Test Performances after Moderate to Severe Traumatic Brain Injury

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Abstract

Objectives: Guidelines on return-to-driving after traumatic brain injury (TBI) are scarce. Since driving requires the coordination of multiple cognitive, perceptual, and psychomotor functions, neuropsychological testing may offer an estimate of driving ability. To examine this, a meta-analysis of the relationship between neuropsychological testing and driving ability after TBI was performed. **Methods:** Hedge's g and 95% confidence intervals were calculated using a random effects model. Analyses were performed on cognitive domains and individual tests. Meta-regressions examined the influence of study design, demographic, and clinical factors on effect sizes. **Results:** Eleven studies were included in the meta-analysis. Executive functions had the largest effect size ($g = 0.60$ [0.39–0.80]), followed by verbal memory ($g = 0.49$ [0.27–0.71]), processing speed/attention ($g = 0.48$ [0.29–0.67]), and visual memory ($g = 0.43$ [0.14–0.71]). Of the individual tests, Useful Field of Vision (UFOV) divided attention ($g = 1.12$ [0.52–1.72]), Trail Making Test B ($g = 0.75$ [0.42–1.08]), and UFOV selective attention ($g = 0.67$ [0.22–1.12]) had the largest effects. The effect sizes for Choice Reaction Time test and Trail Making Test A were $g = 0.63$ (0.09–1.16) and $g = 0.58$ (0.10–1.06), respectively. Years post injury ($\beta = 0.11$ [0.02–0.21] and age ($\beta = 0.05$ [0.009–0.09]) emerged as significant predictors of effect sizes (both $p < .05$). **Conclusions:** These results provide preliminary evidence of associations between neuropsychological test performance and driving ability after moderate to severe TBI and highlight moderating effects of demographic and clinical factors.

Keywords: Cognition, Neuropsychology, Brain injuries, Traumatic, Automobile driving, Executive functions, Attention

INTRODUCTION

Traumatic brain injury (TBI), a significant health problem, represents the leading cause of death for individuals under the age of 45 (Sosin, Sacks, & Smith, 1989). Approximately 1.4 million cases are estimated to occur in the United States each year (Faul, Xu, Wald, & Coronado, 2010). TBI occurs from an impact or sudden acceleration/deceleration resulting in focal or diffuse damage to the brain. Secondary damage can occur via disruptions in cerebral blood flow, intracranial pressure, metabolism, and inflammation (Werner & Engelhard, 2007). Cognitive sequelae are common after TBI, most often identified in the domains of processing speed and attention, executive functions, and memory (Dikmen, Machamer, Powell, & Tempkin, 2003; Mazaux et al., 1997; Millis et al., 2001). Consequently, patients frequently encounter significant barriers to autonomous functioning (Mazaux et al., 1997), including the ability to drive safely (e.g., Cullen, Krakowski, & Taggart, 2014; Sommer et al., 2010). In particular, safe driving behaviours depend on the ability to process visual and auditory stimuli, simultaneously attend to multiple stimuli, shift attention, react quickly to changes in the environment, and make safe decisions.

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Seventy percent of individuals with TBI return to driving within 10 years of injury, given its importance for their autonomy (Ponsford et al., 2014); however, given that cognitive impairments may persist post TBI, returning to the road post injury can present considerable danger and risk of accidents (Bivona et al., 1975; Formisano et al., 2005).

In terms of driving assessment, on-road tests are the most common method of evaluating several driving behaviours (e.g., following traffic rules, making right/left turns, maintaining a safe following distance, merging lanes) in a relatively realistic setting. Unfortunately, on-road tests for patients with TBI pose a risk for both the driver and other road users. Driving simulation is a safer alternative (Cox et al., 2010; Lew et al., 2005), although, at present, this option is mostly limited to rehabilitation settings. The benefit of simulation is the ability to assess not only basic driving behaviours but also complex, challenging, and unpredictable driving scenarios (e.g., left turns at a busy intersection, safely avoiding an accident) while in a safe environment. Driving performance within simulations has been shown to be highly correlated with on-road driving (Lew et al., 2005). More recently, neuropsychological testing is being used as a surrogate evaluation of driving ability; the rationale is to measure the cognitive functions at the crux of driving. It has been already used to predict driving performance and errors in older adults (Lee, Cameron, & Lee, 2003) and individuals with cerebrovascular disease (Marshall et al., 2007).

At present, we have a limited understanding of how neuropsychological test results factor into driving ability following TBI. There is currently no standardized assessment to assess an individual's ability to drive following TBI, which limits physicians' capacity to make informed decisions about driving ability. Research to date has been heterogeneous in terms of the neuropsychological domains probed and specific tests used, hindering the consolidation of a standardized assessment battery. Quantitative reviews with regard to older adults (Mathias & Lucas, 2009), individuals with stroke (Marshall et al., 2007), and individuals with probable Alzheimer's disease and mild cognitive impairment (Hird, Egeto, Fischer, Naglie, & Schweizer, 2016) have identified executive functions, attention, and memory as the most important cognitive domains for the prediction of driving ability. However, no such review has been conducted for patients with TBI.

The main purpose of the present study was to (i) identify the neuropsychological domains most strongly associated with driving ability, and (ii) identify the specific neuropsychological tests that have the strongest associations with driving ability. We also aimed to assess the impact of the driving assessment method (on-road *vs.* simulator), outcome measure (e.g., driving performance, traffic violations), age of patients, years post injury, and TBI severity on the predictive power of neuropsychological tests. Tests of executive function, processing speed/attention, and verbal memory were hypothesized to have the strongest associations with driving ability (Hird et al., 2016; Mathias & Lucas, 2009), with impairments in these domains expected to relate to worse driving behaviours. Simulator assessments (*vs.* on-road), driving performance outcome (*vs.* traffic violations or dichotomous pass/fail), older mean age, shorter post injury time, and more severe injury were hypothesized to be associated with stronger relationships between cognitive test and driving performance.

METHODS

The methods and findings of this meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009). The study was performed in compliance with research ethics regulations at Ryerson University and St. Michael's Hospital.

Literature Search

We searched Medline, Embase, and PsycINFO databases on 25 July 2016 to identify studies that evaluated the predictive properties of neuropsychological tests for driving abilities in patients with TBI. The keywords, along with the appropriate medical subject headings or Psych Thesaurus terms, used were "driving" OR "driving ability" OR "driving behavior" OR "driving test" OR "automobile driving" OR "automobile driving examination" AND "neuropsychology" OR "neurocognition" OR "neuropsychological testing" AND "traumatic brain injury" OR "brain injuries". Note that the exact search terms differed slightly based on the terms available for the three databases. If allowed by database search options, searches were restricted to English language and human participants; reviews, case studies, and abstracts were excluded. An example of our search strategy is included in Appendix A.

To be eligible for inclusion, studies were required to: (a) focus on adults with a history of TBI (although no restriction was placed on mild, moderate, or severe TBI; no studies of patients with a history of mild TBI met our search criteria); (b) examine participants' performance on validated neuropsychological tests; and (c) examine associations between neuropsychological test performance and driving outcomes (with usable data, including mean and standard deviation, correlation r, or F statistics [with a maximum of two conditions]). Studies that met any of the following criteria were excluded: review papers, case studies, conference abstracts, language other than English, and studies that combined TBI with acquired brain injury (e.g., stroke, brain tumours) in analyses.

Following the systematic search and after the removal of duplicates, the resulting abstracts were independently reviewed by P.E. and S.B., and all discrepant decisions were resolved through consensus. Abstracts that appeared to meet inclusion criteria were retained for full-text review. Once eligible articles were confirmed through a full-text review, the reference lists of the included studies were searched for relevant studies, and if any articles were inaccessible, their authors were contacted in an attempt to source such papers.

Data Extraction

The following data were extracted independently, by P.E. and S.B., from each included study, where available: sample size, sample composition (e.g., drivers/non-drivers; patients/controls; patients only), mean participant age, gender composition of sample, mean driving experience of sample (in years), mean Glasgow Coma Scale (GCS) scores, and mean number of years post TBI. Although the demographic information of healthy controls was reported, their neuropsychological and driving performance was not analysed. Data related to associations between neuropsychological test performance and driving outcomes were also extracted and could have included mean neuropsychological test scores (and standard deviations) of driving and non-driving patients and correlations between neuropsychological test scores and driving outcomes. Five studies reported mean and standard deviations (Coleman et al., 2002; Cullen et al., 2014; Gooden et al., 2017; McKay et al., 2016; Radford et al., 2004), and six studies reported correlation *r* (Cyr et al., 2009, Korteling & Kaptein, 1996; Novack et al., 2006; Pietrapiana et al., 2005; Schneider & Gouvier, 2005; Sommer et al., 2010).

Data Synthesis and Analysis

The meta-analyses and meta-regressions were performed using the Comprehensive Meta-Analysis software (version 2.0) (Borenstein, Hedges, Higgins, & Rothstein, 2005). Demographic and clinical information, sample sizes, test means, standard deviations, and correlations were extracted from the included studies. Hedge's *g* with 95% confidence interval (CI) was calculated using a random effects model. Hedge's *g* was calculated based on differences in mean test scores between driver and non-driver patients (driver status was determined generally based on an on-road test), and correlation between test scores of patients and their driving performance (generally traffic violations or self-reported accidents). Significance was set at $p = .05$. Effect sizes of 0.2, 0.5, and 0.8 were considered small, medium, and large, respectively.

Neuropsychological tests were divided into four domains: executive functions, verbal memory, visual memory, and processing speed/attention (note that given the relatively low number of included studies, tests of processing speed and attention were combined). The processing speed/attention domain included: Color Trail Test 1 (time; D'Elia, Satz, Uchiyama, & White, 1996), Trail Making Test A (time; Army Individual Test Battery, 1944), Simple Reaction Time test (Golz, Huchler, Jorg, & Kust, 2004), Choice Reaction Time test (Golz et al., 2004), Useful Field of Vision (UFOV; Ball & Owsley, 1992), Processing Speed subtest, Processing Speed test, Symbol Digits Modalities test (SDMT; Smith, 1982), Visual Search test (Spinnler & Tognoni, 1987), Dot Cancellation (time; Nouri, Tinson, & Lincoln, 1987), and Information Processing A/B tests (Adult Memory and Information Processing Battery – AMIPB; Coughlan & Hollows, 1985). The verbal memory domain included: Logical Memory (immediate; Wechsler, 2009), Verbal Paired Associates (Wechsler, 2009), Story Recall (AMIPB), and List Learning (AMIPB) tests. The visual memory domain included: Design Learning and immediate and delayed Figure Learning (all from the AMIPB). Lastly, the executive functions domain included: Color Trails Test 2 (time), Trail Making Test B (time), Digit Span backwards (Wechsler, 2008), Letter–Number Sequencing (Wechsler, 2008), UFOV divided and sustained attention subtests, Paced Auditory Serial Addition Test 1/2 (Gronwall & Sampson, 1974), Mental Control (Wechsler Adult Intelligence Scale III; Wechsler, 1997), and the Stroop test (Stroop, 1935). Immediate and delayed recall tests were grouped together in the memory domains due to an insufficient sample size.

Analyses were also performed for individual tests with at least two data points: UFOV selective and divided attention subtests, Trail Making Tests A and B, Digit Span backwards, Simple Reaction Time test, Choice Reaction Time test, and the SDMT.

The driving outcomes included were: on-road or simulator driving performance, documented traffic violations and accidents, and rate of return-to-driving. The advantage of using actual driving records is that they provide a measure of real-world outcomes and thus have strong ecological validity. Although the amount of driving the patient does (e.g., kilometres driven per month) and the patient's pre-injury driving records are important considerations when interpreting post-injury driving records (Haselkorn, Mueller, & Rivara, 1998), most studies unfortunately did not comment on these factors.

The relations between effect sizes and (i) driving assessment method (driving performance in either on-road or simulator tests, or self-reported traffic violations); (ii) outcome measure (e.g., driving performance, traffic violations); (iii) age of patients; (iv) years post injury; and (v) TBI severity were separately examined using a series of linear meta-regression models. Study quality was evaluated using the Effective Public Health Practice Project Quality Assessment Tool (Armijo-Olivo, Stiles, Hagen, Biondo, & Cummings, 2012). Egger's test was used to examine funnel plot asymmetry (Egger, Smith, Schneider, & Minder, 1997). This test examines the association between observed effect sizes and their corresponding sample variances. A significant result indicates a non-zero regression intercept and suggests potential publication bias. Duval and Tweedie's trim and fill was used to estimate and correct plot asymmetry due to missing studies and more extreme results (Duval & Tweedie, 2000). This test plots the inverse effect sizes against their standard errors, and "trims" extreme results until the plot is more symmetric around the mean. This creates a new, estimated mean effect size.

RESULTS

Literature Search

A flow chart illustrating the study identification process is presented in Figure 1. The systematic search yielded 59 studies. After removing 16 duplicates, the remaining 43 abstracts were screened. Twenty-seven of these abstracts appeared to

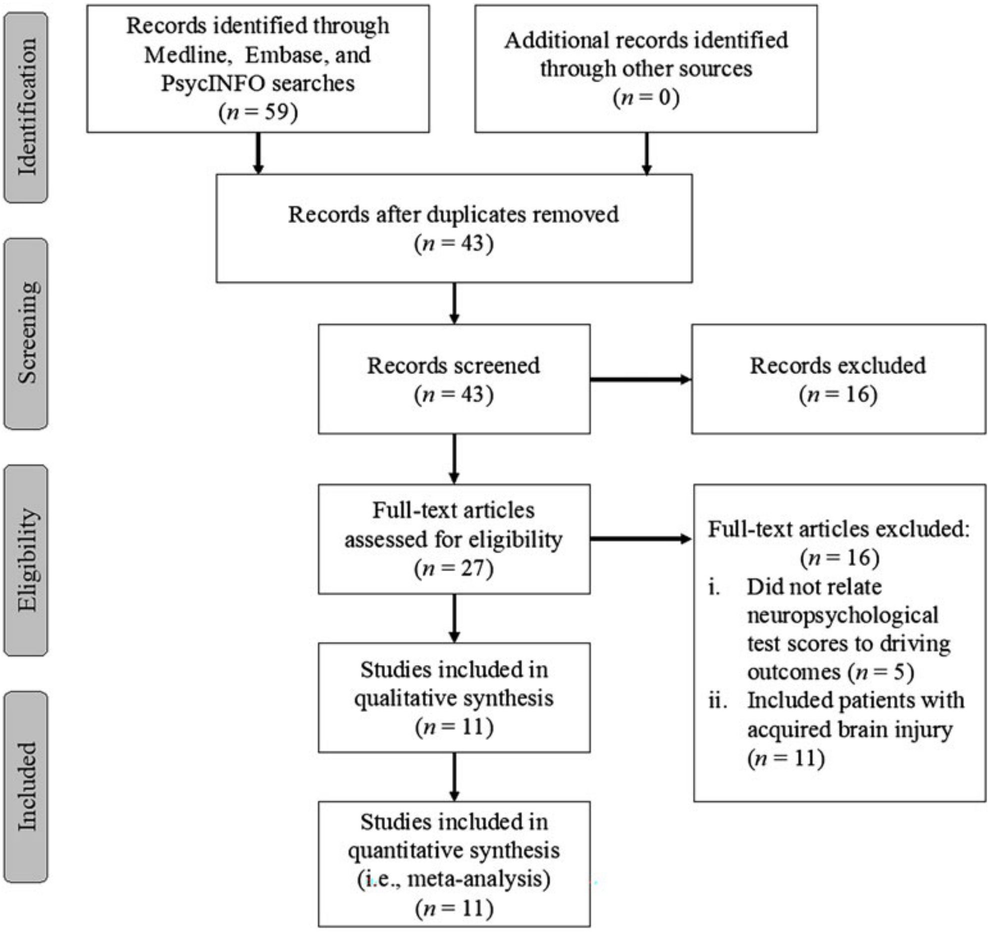


Fig. 1. Flow chart of included studies.

meet the inclusion criteria and were retained for full-text review. Following a full-text review, a total of 16 articles were excluded for not relating neuropsychological test scores to driving outcomes (*n* = 5) or for including patients with acquired brain injuries such as stroke or brain tumours (*n* = 11). Ultimately, 11 studies met the inclusion criteria and were included in the meta-analysis, all cohort designs (Coleman et al., 2002; Cullen et al., 2014; Cyr et al., 2009; Gooden et al., 2017; Korteling & Kaptein, 1996; McKay, Liew, Schonberger, Ross, & Ponsford, 2016; Novack et al., 2006; Pietrapiana et al., 2005; Radford, Lincoln, & Murray-Leslie, 2004; Schneider & Gouvier, 2005; Sommer et al., 2010). Eight of the 11 studies scored as "moderate" on the publication quality scale, and three scored as "weak" quality (study ratings indicated in Table 1).

Sample Characteristics

The sample characteristics are presented in Table 1. A total of 587 patients with TBI (in studies that divided patients into drivers and non-drivers, 185 were classified as drivers and 126 as non-drivers) were included in the analyses. The demographic information of the 56 healthy controls was described. The mean (*SD*) age of all patients was 36.3 (14.1), 39.7 (14.4) for driving patients, 38.1 (14.6) for non-driving patients, and 26.8 (10.9) for controls. Of the patient group, 453 were males (134 females); and of the control group, 26 were males (30 females). The mean (*SD*) years of education for patients (given the differing methods of reporting education attainments, data across patients were collapsed for this calculation) was 12.3 (3.1). Details on the length of post-traumatic amnesia among patients are reported in Table 1. The mean GCS score for driving patients was 7.9 (4.0), and 8 (3.9) for non-driving patients (both falling in the moderate–severe range). None of the included studies recruited patients with mild TBI. The mean years passed between the injury and testing was 4.2 (4.3) for all patients – 2.9 (3.2) for drivers and 4.5 (3.5) for non-drivers. Seven studies used an on-road test to assess driving ability (Cullen et al., 2014; Gooden et al., 2017; Korteling & Kaptein, 1996; McKay et al., 2016; Novack et al., 2006; Radford et al., 2004; Sommer et al., 2010); three used medical chart data or self-report to obtain a history of accidents or traffic violations (Coleman et al., 2002; Pietrapiana et al., 2005; Schneider & Gouvier, 2005); and one utilized a simulator (Cyr et al., 2009).

Neuropsychological Domains

Pooled effect sizes for all four cognitive domains were significantly different from zero, indicating that significant

Table 1. Study demographics and quality ratings

Study	Participants[a]	*N*	Age[b]	Male/ female	Education[b]	Years of driving experience[b]	GCS[b]	PTA	Years post TBI[b]	Quality rating
Coleman et al., 2002	NDR	38	41.3 (13.4)	57/14	11.6 (1.2)	–	10.8 (3.4)	–	4.7 (2.5)	Moderate
	DR	33	38.8 (12.5)	–	11.7 (2.2)	–	10.5 (3.7)	–	4.9 (2.8)	–
Cullen et al., 2014	NDR	19	49.0 (14.9)	18/1	53% ≤ high school, 31% university	–	6.5 (3.9)	–	5.8	Moderate
	DR	19	48.5 (14.3)	12/7	21% ≤ high school, 68% university	–	7.0 (3.3)	–	8.3	–
Cyr et al., 2009	Patients	17	39.5 (11.0)	11/6	15.5 (2.1)	–	–	48 h to 4 months	6.3 (5.8)	Moderate
	CTR	16	38.7 (13.5)	10/6	16.9 (2.3)	–	–	–	–	–
Gooden et al., 2017	NDR	13	41.9 (15.8)	8/5	15.4 (2.7)	20.5 (14.6)	8.0 (4.2)	30.1 (29.4) days	1.8 (0.9)	Moderate
	DR	24	40.8 (14.1)	20/4	14.1 (2.4)	22.8 (14.5)	7.6 (5.0)	32.4 (30.2) days	1.3 (1.2)	–
Korteling & Kaptein, 1996	Patients	38	29.8 (10.9)	33/5	–	–	–	–	–	Weak
McKay et al., 2016	NDR	21	35.5 (15.7)	18/3	–	13.2 (15.8)	–	23.5 (26.2) days	1.5 (0.9)	Moderate
	DR	78	42 (14.3)	67/11	–	22.4 (14.34)	–	23.5 (26.2) days	0.5 (0.3)	–
Novack et al., 2006[c]	Patients	60	33.0 (16–68)	38/22	12.7 (3.3)	–	–	All >1 week	1.5 (0.2–19)	Weak
Pietrapiana et al., 2005	NDR	35	28.9 (7.7)	54/12	10.5 (3.3)	10.3 (7.2)	5.9 (2.0)	–	6.2 (4.4)	Moderate
	DR	31	28.5 (10.8)	–	10.7 (3.3)	10.3 (9.9)	5.9 (1.8)	–	5.0 (2.7)	–
Radford et al., 2004	Patients	52	39.1 (12.8)	44/8	–	18.5 (12.4)	–	–	2.3 (1.7)	Moderate
Schneider & Gouvier, 2005	Patients	40	22.0 (4.1)	16/24	2.5% 1st-year, 15% 2nd-year, 32.5% 3rd-year, 50% 4th-year university	–	–	77.5% <5 min, 12.5% 5–60 min, 10% 1–24 h	7.1 (5.1)	Weak
	CTR	40	22.0 (4.0)	16/24	7.5% 1st-year, 17.5% 2nd-year, 30% 3rd-year, 45% 4th-year university	–	–	–	–	–
Sommer et al., 2010	Patients	9	35.9 (9.7)	57/12	[d]13% level 2, 52.2% level 3, 21.7% level 4, 13% level 5	–	–	–	5.1 (5.7)	Moderate

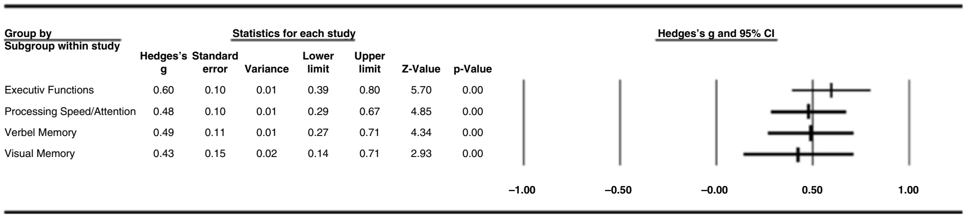
Abbreviations: CTR, controls; DR, drivers; GCS, Glasgow Coma Scale; NDR, non-drivers; PTA, post-traumatic amnesia; SD, standard deviation; TBI, traumatic brain injury.

[a] Studies either included patients and controls, or divided patients into drivers and non-drivers.

[b] Mean (SD).

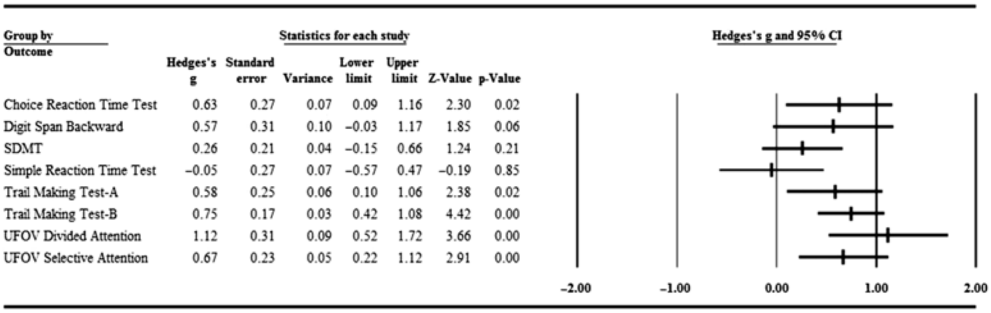
[c] Mean and range are provided.

[d] According to the educational system of Germany.



Group by Subgroup within study	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Executiv Functions	0.60	0.10	0.01	0.39	0.80	5.70	0.00
Processing Speed/Attention	0.48	0.10	0.01	0.29	0.67	4.85	0.00
Verbel Memory	0.49	0.11	0.01	0.27	0.71	4.34	0.00
Visual Memory	0.43	0.15	0.02	0.14	0.71	2.93	0.00

Fig. 2. Effect sizes of neuropsychological domains.



Group by Outcome	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Choice Reaction Time Test	0.63	0.27	0.07	0.09	1.16	2.30	0.02
Digit Span Backward	0.57	0.31	0.10	–0.03	1.17	1.85	0.06
SDMT	0.26	0.21	0.04	–0.15	0.66	1.24	0.21
Simple Reaction Time Test	–0.05	0.27	0.07	–0.57	0.47	–0.19	0.85
Trail Making Test-A	0.58	0.25	0.06	0.10	1.06	2.38	0.02
Trail Making Test-B	0.75	0.17	0.03	0.42	1.08	4.42	0.00
UFOV Divided Attention	1.12	0.31	0.09	0.52	1.72	3.66	0.00
UFOV Selective Attention	0.67	0.23	0.05	0.22	1.12	2.91	0.00

Fig. 3. Effect sizes of neuropsychological tests.

group differences in driving outcomes as a function of neuropsychological test performance were identified for each neuropsychological domain. The largest pooled effect was calculated for executive functions, with results indicating a medium effect size ($g = 0.60$ [0.39–0.80], $k = 20$; Figure 2). Verbal memory yielded the second largest effect size ($g = 0.49$ [0.27–0.71], $k = 7$), followed closely by processing speed/attention ($g = 0.48$ [0.29–0.67], $k = 17$), and then visual memory ($g = 0.43$ [0.14–0.71], $k = 4$).

Egger's regression did not indicate a significant funnel plot asymmetry in any of the domains (all $p > .05$), suggesting the overall effect was robust. The trim and fill adjusted the effect size of verbal memory to $g = 0.52$ (0.31–0.74). The trim and fill did not adjust effect sizes for executive functions, processing speed/attention, and visual memory, suggesting symmetrical distribution around the funnel plot.

Neuropsychological Tests

The effect sizes of individual tests were similar to that of the domains, as tests of executive functions had the largest effect sizes (Figure 3). Large effects were found for UFOV divided attention ($g = 1.12$ [0.52–1.72], $k = 2$) and Trail Making Test B ($g = 0.75$ [0.42–1.08], $k = 5$), and medium effects for UFOV selective attention ($g = 0.67$ [0.22–1.12], $k = 3$). The effect size for Digit Span backwards was not significant by a small margin ($g = 0.57$ [−0.03 to 1.17], $k = 3$). Tests of processing speed/attention had medium effects: $g = 0.63$ (0.09–1.16), $k = 2$ for the Choice Reaction Time test, and $g = 0.58$ (0.10–1.06), $k = 2$ for Trail Making Test A. Lastly, the effects of the Simple Reaction Time test ($g = -0.05$ [−0.57 to 0.47], $k = 2$) and SDMT ($g = 0.26$ [−0.15 to 0.66], $k = 3$) were not significant.

Only the analyses for the Trail Making Test B, SDMT, and UFOV selective attention tests had sufficient sample sizes to conduct publication bias analyses. Egger's regression did not indicate significant funnel plot asymmetry in any of the tests (all $p > .05$), suggesting the overall effect was robust. The effect sizes of SDMT and UFOV selective attention were not altered in the trim and fill, suggesting a symmetrical funnel plot distribution. The trim and fill adjusted the effect size of the Trail Making Test B to $g = 0.47$ (0.01–0.94).

Demographic, Clinical, and Assessment Variables

The driving assessment method (driving performance or self-reported traffic violations), outcome measure (on-road or simulator driving performance, traffic violations, driving test pass/fail), mean age, mean years post injury, and mean GCS scores were entered into meta-regressions to evaluate whether they influence the relationship between neuropsychological test performance and driving outcome. Years post injury was the strongest predictor of effect sizes: $\beta = 0.11$ (0.02–0.21), $p < .05$. Age also emerged as a significant predictor of effect sizes: $\beta = 0.05$ (0.009–0.09), $p < .05$. Neither the driving assessment method ($\beta = 0.13$ [−0.18 to 0.44], $p = .40$), the outcome measure ($\beta = -0.027$ [−0.58 to 0.52], $p = .92$), or GCS score ($\beta = 0.046$ [−0.07 to 0.16], $p = .44$) significantly predicted effect sizes.

DISCUSSION

Ensuring the safety of drivers and other road users is paramount; however, guidelines for the assessment of driving competence in individuals with TBI are lacking, let alone assessment batteries tailored to specific neurological populations. In an effort to contribute to a more cohesive understanding of driving ability evaluations, the literature examining the relationship between neuropsychological testing and driving ability after TBI was quantitatively reviewed. Additionally, demographic, clinical, and driving assessment variables were examined as moderators of the above relationship. Measures of executive functions were found to have the strongest relationships with driving outcomes, with results indicating a medium effect size. Verbal memory and processing speed/attention also had medium effects, although somewhat smaller than that of executive functions. Visual memory had a small effect. Individual test analyses mirrored these results: tests probing different aspects of executive functions – Trail Making Test B, UFOV divided and selective attention subtests – evidenced the largest effect sizes. The Choice Reaction Time test and Trail Making Test A, both measures of processing speed/attention, had comparatively smaller effect sizes. The effects of the Simple Reaction Time test, Digit Span backwards, and SDMT were not significant. In the meta-regressions, the number of years post injury and age emerged as significant predictors of effect sizes, whereas driving assessment methods, outcome measures, and GCS scores were not significant predictors.

Measures of executive functions had the largest effect size by a small margin when differentiating safe *versus* unsafe driving. One potential explanation is the role that executive functions play prior to entering hazardous situations: making decisions to maintain safe driving circumstances (e.g., avoid driving in poor weather conditions), planning (e.g., establishing a route), inhibiting distracting stimuli (e.g., ignoring billboards), working memory (e.g., remembering which streets have been passed prior to an upcoming turn), and task switching (e.g., switching between spatial navigation and executing a safe turn). Conversely, although processing speed/attention might influence focus and the speed with which drivers can react in a dangerous situation, this alone may not be sufficient to avoid an accident. Thus, it is possible that obviating dangerous situations through planning, inhibition, and other executive functions has a greater impact on avoiding accidents compared with greater focusing and faster information processing during a dangerous situation. Interestingly, the domain of verbal memory emerged as having the second largest effect size, but the reason for this is not entirely clear. Memory is important for operating a car and obeying traffic rules, but there is a paucity of research linking specific verbal memory processes to driving behaviours (most studies simply implement memory tasks in dual-task designs). Spatial and visual memory would be more likely candidates, but tests of the former were not administered in the included studies, and visual memory had the smallest effect size.

Relative differences in effect sizes notwithstanding, the contribution of both processing speed/attention and executive functions to driving is delineated in a three-level hierarchy model (Michon, 1989). This model contains three cooperative levels: operational, tactical, and strategic. At the lowest level, operational performance relies on perceptual and motor functions, including visuospatial functioning, motor strength and sequencing, and processing speed. The next level, tactical, encompasses planning, task switching, decision making, and inhibition in limited timeframes while driving. This level is one of two levels that relies on executive functions to navigate, control attention, maintain multiple simultaneous cognitive processes, and make decisions based on dynamic driving conditions. Lastly, the strategic level primarily involves planning without a time limit; also engaging executive functioning, its primary functions are planning and decision making prior to driving (e.g., planning routes, making decisions based on weather and other driving conditions). Notably absent were tests of vision and motor dexterity. It is likely that the patients included in the studies on driving ability were required to have intact vision and motor abilities, although this was not explicitly described in the included studies.

Our ability to investigate the moderators of the relationship between neuropsychological test performance and driving outcomes was limited, due to the paucity of information that studies provided on clinical and demographic variables (e.g., only three provided GCS scores) and the small number of samples overall. However, the number of years post injury and age variables emerged as significant moderators. Specifically, effect sizes were larger among samples with older participants and those who were assessed at longer durations (years) post injury. The greatest cognitive improvements are expected within the first year post injury, but impairments may persist for more than a decade following a TBI (Draper & Ponsford, 2008; Novack, Alderson, Bush, Meythaler, & Canupp, 2000). Hence, one might expect a stronger association between neuropsychological testing and driving performance closer to the time of injury. However, a statistical explanation may account for the opposite finding; patients with persistent, significant cognitive impairments may be a more homogeneous group, and the tighter variability of their data may have allowed for a stronger association with effect sizes. With regard to the impact of age, it is possible that the driving performance of younger adults is relatively less impacted by some of the physical (e.g., diminished functioning) and cognitive (e.g., aging-related) factors that impact older adults, potentially leading to a ceiling effect in driving outcomes (i.e., insufficient variability) among younger adults. In both cases, findings will need to be re-examined once additional research has been conducted with larger and more diverse samples.

Lastly, all of the included studies exclusively recruited moderate and severe TBI cases, and none with mild TBI (concussion). Concussions are more common than moderate to severe TBI, and as such, the evaluation of the driving ability of this population is important. That said, cognitive deficits tend to be milder and briefer, and the value of neuropsychological testing in predicting the driving ability is unclear given an underdeveloped literature. There is evidence of impaired hazard perception of patients with mild TBI (within 24 h of trauma) while watching driving videos (Preece, Horswill, & Geffen, 2010). Patients with mild TBI also demonstrate more driving errors, which are correlated with the performance on processing speed, visual memory, and motor speed measures (Schmidt et al., 2017). Patients with a history of mild TBI also self-report more traffic violations and vehicle collisions (Bernstein & Calamia, 2018) and using more strategies to compensate for driving difficulties (Bottari, Lamothe, Gosselin, Gélinas, & Ptito, 2012) relative to those with no history of concussion. An avenue of future research should focus exclusively on concussed patients to elucidate this relationship between neuropsychological assessment and driving ability, especially in the acute phase of recovery given the evidence of a typical rapid recovery from concussion.

Limitations

First and foremost, the small sample of studies that met the inclusion criteria meant that some analyses were underpowered (e.g., GCS analyses; some individual test analyses had two or three data points). This reduced the applicability and generalizability of the results. Moreover, there are variations in the types of tests that were included in each study; although most studies included at least one measure of executive functions, others did not always include measures of memory or attention/processing speed. Similarly, due to some heterogeneity in the way that driving ability (e.g., driving performance, history of accidents, traffic violations) was operationalized across studies, the outcome measures could not be perfectly overlapped. This issue, as has been noted elsewhere, hindered the consolidation of guidelines on neuropsychological factors in driving ability (Mazaux et al., 1997; Ponsford et al., 2014).

Aside from the GCS meta-regression, other factors, including loss of consciousness and neuroimaging results, were not provided by included studies and hence could not be analysed as moderators. This is a notable limitation in neuropsychological practice, given that injury variables have important implications on the severity of cognitive and functional impairment, as well as prognosis. Similarly, information on premorbid or comorbid conditions was sparse (only Pietrapania et al., 2005 explicitly excluded participants with significant psychiatric comorbidity), but is important for the interpretation of cognitive and functional profiles.

Future Directions

Our review identified multiple avenues for future investigations. First, across studies, the average time elapsed between TBI and testing was approximately 4 years, which allowed for ample recovery time and rehabilitation opportunities. Cognitive functions of patients several years after injury must be undoubtedly different than those at a more proximate time point. Hence, adopting a diverse range of time frames between TBI and neuropsychological testing, particularly with a greater representation of patients at a time point closer to the time of their injury (e.g., 1–2 years), would inform both the potential driving deficits during the early stages as well as the time course of changes in cognitive functioning and driving.

Furthermore, there was a general lack of information on post-injury driving habits (e.g., driving frequency, driving situations avoided). Although many patients had their licences reinstated and/or resumed driving, it was unclear whether they completely returned to their pre-injury routines. If not, then the residual cognitive changes (or psychological or physical) may impact patients in untested ways. Collecting such data could help better elucidate the link between TBI sequelae and driving abilities and habits.

Similarly, a more stringent and systematic collection of demographic and clinical variables will be important to explore additional links between cognitive and driving functions. For instance, the GCS score, a key factor in TBI management, would be an important feature to account for when examining the cognition–driving relationship. That said, a better capturing of demographic and clinical variables should be coupled with larger samples. This would provide greater variances and consequently more accurate and meaningful statistics.

CONCLUSIONS

The results of this meta-analysis demonstrate that neuropsychological testing is a promising avenue in the evaluation of driving ability of patients after TBI. This leaves the question of what test battery ought to be ideal for neuropsychological evaluation. Although more research is needed, some preliminary patterns emerged. In general, tests of executive functions had a larger effect size relative to other cognitive domains when differentiating between safe and unsafe driving measures. Measures of verbal and visual memory and attention/processing speed also emerged as important domains. This suggests that the abilities to effectively execute higher-order processes, encode and recall important information (e.g., traffic rules), allocate attention, and process information quickly are critical for safe driving. At the very least, neuropsychological testing of these domains should be included in an assessment battery, possibly with an emphasis on tests of executive functions (e.g., Trail Making Test B, UFOV selective and divided attention). Of note, although some UFOV subtests had large effect sizes, this test is not commonly used in clinical practice. This is in part because neuropsychologists do not frequently use computerized tests in practice, and this test does not have the same rigorous normative data that many other neuropsychological tests have. However, it may still be considered a useful tool, especially in guidelines on return-to-driving after traumatic brain injury. In conclusion, by examining the initial evidence of the relationship between cognitive impairment and driving ability, this study provides impetus for future research to examine the clinical applications and predictive value of individual neuropsychological tests in driving assessments.

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SUPPLEMENTARY MATERIALS

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