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To drive or not to drive (after TBI)? A review of the literature and its implications for rehabilitation and future research

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Abstract. Development of reliable procedures to assess fitness to safe driving after traumatic brain injury (TBI) is a crucial step in rehabilitation. However, prior studies are highly inconsistent in the choice of measures recommended for predicting driving fitness from different pre-driving measures. In the present paper the relevant literature is reviewed with the aim of shedding light on the reasons for these inconsistencies. The discrepant results reflect investigative choices which differ in five aspects: (1) the type of predictors used as pre-driving screening; (2) the type of measures considered as the criterion for the determination of fitness to drive after TBI; (3) the severity of the TBI in the sample of patients studied; (4) the extent of the neural structures damaged by TBI and the overlap of these areas with those involved in driving tasks; (5) the length of the follow-up considered. The strengths and weaknesses of the different methods and measures are discussed with their implications for future research and clinical rehabilitation. Encouraging findings come from recent studies that combined together medical, psychosocial, and personality measures, thereby improving the explanatory power of the predictors used. The use of post-injury driving fitness measures with great ecological and external validity seems equally promising in assessing actual driving in the real world.

Keywords: TBI, brain injury, driving safety, rehabilitation

1. Introduction

Traumatic Brain Injury (TBI) is one of the most frequent causes of acquired disability among young persons under the age of 35, and frequently leads to motor, cognitive, and behavioral deficits. For adults recovering from TBI, the return to driving a motor vehicle is an extremely important aspect in resuming a normal lifestyle. However, the issue of resuming driving after TBI also constitutes a problem of safety and public health, considering the great number of people involved, whether directly (parents and relatives) or indirectly (other drivers). Indeed, about 50% of survivors of TBI resume driving, although nearly two thirds of them do so without specific medico-legal examination or formal evaluation [2,7,13,19,60,62,70,80]. Lacking a standard method for the assessment of driving capabilities, specialists have developed their own procedures. These procedures differ in many aspects, but generally include a pre-driving examination and an on-road evaluation as the criteria for the determination of fitness to drive [24–26]. Yet behind-the-wheel tests are still not part of an established common procedure in many countries, and are not easy for hospitals or rehabilitation centers to organize [12,35]. Furthermore, they are costly for patients in terms of money, time and energy required [11]. As a consequence, researchers have tried to identify a number of effective pre-driving measures to predict future fitness to drive of patients recovering from TBI, hence providing a valuable screening tool to

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rehabilitators and clinicians. Unfortunately, the results of various studies in predicting driving fitness from different pre-driving parameters are highly inconsistent, and range from a reported predictive power of 20% to 94% of explained variance (the predictive power refers to the proportion of variance of the driving fitness measure that can be explained by predictor variables) [2, 10,23–28,30,41,43,44,57,67,71].

In the present paper the relevant literature has been reviewed with the aim of shedding light on the reasons for these inconsistencies and of outlining the strengths and weaknesses of the different methods and measures used by various studies. We thus hope to help rehabilitators to take better decisions when choosing among available pre-driving predictors and driving fitness measures and to provide valuable insights for future research aimed at detecting a number of reliable pre-driving predictors of the fitness to safe driving after TBI.

The foregoing inconsistencies reflect different investigative choices in one or more of the following topic areas (see also Appendix 1).

1.1. The different predictors of post-injury driving fitness

Predictors have been taken from five different sources: (1) simulator and off-road closed course evaluating driving performance on basic car maneuvering skills (e.g., driving around cones, straight-tracking or braking); (2) demographic and biographic variables (age, driving experience before TBI, education and years post-injury); (3) medical data (e.g., Glasgow Coma Scale, coma duration, etc.); (4) neuropsychological and behavioral tests assessing cognitive capacities, perceptual-motor skills, and functional abilities; (5) measures related to higher order cognitive functions, such as awareness of the deficits, or to personality traits and pre-injury driving style.

Even though Galski et al. [26] and Odenheimer et al. [57] reported that the closed-course or simulator performance of their subjects accounted for, respectively, 63% and 36% of the variance in the on-road examination, in most cases closed-course or simulator evaluations yielded little useful information about actual driving behavior observed on public roads where other drivers are present [24,27,28,71]. Similar results have been found for demographic variables that did not show any significant correlation with the open-road driving fitness measure [10,30,43,61,71].

Contradictory results have been obtained using medical data to predict driving fitness. For instance, in some studies, the subjects' rating on the Glasgow Coma Scale (GCS), the Functional Independence Measure (FIM), as well as coma duration or clinical parameters of injury severity, were relevant in predicting the ability to drive properly and competently after TBI [13,22,43]. By contrast, other studies failed to report significant correlations of these pre-driving measures with post-injury driving fitness [10,25,30,61,71].

Neuropsychological tests are generally considered useful tools and have shown some value in the assessment of driving fitness, especially those tests involving focused and divided attention, information processing speed, working memory, and perceptual-motor skills [4,10,25,26,28,30,39,43,46,49,67,68,71, 74,80]. Yet, the specific predictive power of these neuropsychological measures is far from clear, reflecting the wide differences among the tests selected and the various measures of driving fitness used as the criterion variable (see below).

Most of the studies so far reviewed have tended to consider driving a perceptual-motor skill or a task based on relatively elementary functions and have consequently adopted tests tapping these abilities [16]. Such aspects are obviously important in assessing the driving fitness of post-TBI subjects. However, in order to formulate realistic judgments about patients' actual ability to drive, it is also necessary to consider other higher-order capacities. The lack of consistency in the measures reported as valuable predictors of driving fitness among different studies can be partially explained by the limited consideration given to these aspects [25,61,78,80]. In fact, driving safely is much more than just mechanically operating a vehicle, and can never be reduced to automatic behaviors. Driving requires planning, concentration, inhibition of distractors, foresight, anticipation, problem-solving capacities, the ability to interpret rapidly complex arrays of multimodal stimuli, and prompt, effective and calm reactions. Some post-TBI subjects have deficits in one or more of these domains and may have loss of emotional control under certain circumstances [1,5,6,18,21, 42,47,73,75,77]. Others may also be unaware of their deficits and may subjectively feel perfectly able and fit to drive again [20,56,59]. Conversely, basic deficits at the motor level and the consequent risk of crashes can be moderated by higher-order cognitive abilities such as self-awareness of the deficits induced by the injury [10,48,53,64–66]. It follows that patients with severe physical or cognitive disabilities, and an objective high risk factor for accidents, can be at low risk if they appreciate the relevance of their deficits and act consequently [10]. According to this view, several theoretical approaches to modelling driving behavior (like motivational [63] or cybernetic models [26]) have addressed functional and higher-order cognitive aspects rather than perceptual-motor skills alone (see Ranney [63] for a review). Michon [50,51] proposed a conceptual model that schematizes driving into three main hierarchically interconnected levels: strategic, tactical, and operational level. The strategic level deals with decisions connected with driving which may be taken without time constraint (e.g., day and hours for traveling, route to be followed, stops for petrol, food, rest, etc.). At this level, dealing with danger depends on risk acceptance. A safe driver can compensate for lower level impairments by taking good strategic traffic decisions; for example, choosing less crowded roads or avoiding rush-hour traffic. The tactical level has to do with driving planning, flexibility and adaptation (e.g., adequate speed and limits, decisions on changing lane, overtaking, slowing down, etc.). These operations must be done in a limited timeframe and, among other abilities, require focused attention, adequate judgment and anticipation, inhibition of distractors, and realistic awareness of self and environment. The operational level mainly concerns the perceptual and mechanical ability to use a motor vehicle and depends on training, visuo-perceptual spatial scanning, motor strength and sequencing, rapidity of primary reaction time, etc.

Recently, several studies have addressed higher-order cognitive and personality aspects in the attempt to consider together the operational, tactical, and strategic levels [2,10,15,26,28,43,61,64–66]. Brower and Van Zomeren [8], for example, recognized social responsibility as an important additional factor in the assessment of driving fitness. Coleman et al. [10], Rapport et al. [64–66], and Galski and co-authors [28] reported that the risk of car accidents was more accurately predicted by measures of patients' awareness of deficits than by measures of physical impairment or low-level perceptive-motor skills. In the study of Galski et al. [26] the driving instructor who rated patients' performance in an open-road examination, also considered critical behaviors such as impulsivity, distractibility, anxiety, or inattention. In an attempt to evaluate the influence of factors that go beyond the direct impact of the injury, Pietrapiana et al. [61] studied the relationship between the driving performance of 31 patients who had returned to driving after TBI and factors such as pre-injury personality traits or pre- injury driving style. The authors reported that, overall, premorbid measures explained up to 72.5% of the driving performance in the real world after TBI evaluated on the number of car accidents and traffic rules violations. Furthermore, the premorbid factors turned out to be far better predictors than demographic, biographic, medical or neuropsychological measures collected on the same sample.

Another pre-injury personality trait recognized as an important predictor of the driving style and car accidents rate is conscientiousness. Conscientiousness is one of the five broad domains taken by the Big Five Taxonomy [29] to organize personality traits and refers to individual differences in the propensity to follow socially prescribed norms and rules (especially for impulse control), to be task- and goal-directed, and to delay gratification [37]. Recently Bogg and Roberts [3] carried out a meta-analysis on conscientiousness-related traits and related behaviors as possible contributors to mortality, including risky driving. The sample contained 21 studies (out of 194) on risky driving for an overall sample of 10,171 drivers. Results showed that the domain of conscientiousness was negatively correlated with risky driving. That is; the more a subject was rated as conscientious, the less his/her driving style was risky. A final psychological factor highly involved in crash risk is hazard-perception ability. According to Elander et al. [14] slower detection of hazards increases car crash frequency, due to impaired abilities to identify visual targets in a complex background and to rapidly shift attention.

To summarize, different predictors have been evaluated in assessing fitness to drive after TBI. The most promising are medical and neuropsychological measures (like parameters of injury severity and measures of perceptual-motor functions, respectively), but uncertainty about their specific role arises from differences in the choice of tests and of adequate measures of driving fitness. Furthermore, most tests have accounted for basic functional and perceptual-motor skills not as often for the other higher-order cognitive and psychosocial capabilities indispensable for safe driving. A growing body of evidence indicates the influence of premorbid psychosocial background and habits on post-injury functioning and behavior. Encouraging results thus come from recent studies that, considering different sources of information from medical to psychological domains, have improved the explanatory power of the predictive measures used.

1.2. Measures for assessing actual post-injury driving fitness

Driving outcome measures are those parameters used to assess the actual fitness to drive after TBI. It is worth noting that these measures are themselves indexes thought to reflect actual driving fitness in the real world for long periods.

Closed-course and off-road evaluations have been criticized, when used as post-injury driving fitness measures, because they do not provide information about a driver's ability in the real world where interaction with other cars and complex traffic patterns is required [8, 26–28,71,72]. Apart from the lack of ecological validity, some studies indicate that closed courses have limited correlation with on-road evaluations [26–28, 71].

The majority of research in the field used on-road evaluations as a direct measure of driving abilities (see Fox et al. [24] for a review). This choice is probably related to the fact that on-road assessment is the commonly accepted licensing test for normal persons learning to drive. However, as noted earlier, on-road assessment is itself a measure to predict driving fitness in the real world on a long-term basis that critically depends on several other factors such as environmental conditions, intensity of traffic, general state of the driver, car performance and frequency of use that go beyond the limited timeframe of the assessment. Surprisingly, a direct relationship between on-road assessment and real-world driving performance has been taken for granted. Few studies have attempted to establish the validity and reliability of this link by evaluating, for instance, the value of on-road testing for predicting traffic violations or car accidents [10]. There are several theoretical and empirical reasons supporting a skeptical position that criticizes the validity of on-road evaluations. For instance, from the theoretical perspective put forth by Michon [50,51], on-road assessments do not elucidate the strategic level of driving skill that includes all the decisions made before actual driving starts [24,80]. Another difficulty in assuming that on-road tests are valid arises from the consideration that highly-skilled drivers sometimes have above-average accident rates. Indeed, drivers do not always drive as they did during their licensing test [52,68,81]. These arguments undermine the supposed external validity of on-road assessment. Additional sources of variability in the results obtained from on-road testing arise from the extremely different procedures used in assessing on-road performance that are consequently hardly comparable. In general, little attention has been devoted to reliability or standardization of the on-road assessment [24]. Some studies used a short informal test [24,26,43], whereas others adopted a standardized course with predetermined maneuvers [15,31,38,71]. In Sivak and colleagues' study [71], a 17-km course was standardized for driving maneuvers, traffic density and difficulty, then driving performance was evaluated on 144 predetermined behaviors. Engum and collaborators [15] rated 144 driving maneuvers on six basic actions. Korteling and Kaptein [43] judged subjects' driving performance in a moderately formalized test on five dimensions (temporal and attentional aspects, flexibility, technical driving and traffic rules) further subdivided into other elementary driving aspects singly rated on a scale ranging from 2 to 9. Fox and coauthors [25] observed five areas of driving performance such as planning and judgment, vehicle positioning, reaction time, speed control and observation. Galski et al. [26] scored specific actions and other observable behaviors divided in: operations that come before driving, driving actions, and other cognitive and behavioral activities.

Equally different among various studies are the scoring approaches that alternatively calculated the number of correct maneuvers, or rated predetermined driving actions on a 5 or 8 point scale [43,83]. Other authors considered the time taken for various actions [4] or used a pass-fail rating for each maneuver [26–28,36,54, 57] or even adopted a qualitative description of driving skills [25,40,69]. Many studies used one rater in the car during on-road assessment (a driving instructor or an occupational therapist) [27,39,40,69] whereas others used two or more raters [25,36,57,83]. In addition, most research that adopted the on-road evaluation as the driving fitness measure has included raters who were not blind to the diagnosis of the subjects, thus possibly introducing a systematic bias. One last criticism of on-road tests relates to the issue of test-retest reliability. Jones [38] administered his highly standardized test to 194 high-school driving students and then re-tested 67 of them 2 weeks later: test-retest correlation was only 0.40. Van Zomeren et al. [79] and Galski et al. [28] found that the overall rating of driving fitness did not relate to single items calculated in terms of driving error score.

Recent studies tried to develop new driving fitness measures that could be more informative than on-road evaluations about actual driving ability of post-TBI patients in everyday life [10,13,17,22,61]. Car accidents or traffic violations rate (or both) which occurred since the return to driving after TBI have been used as driving fitness measures. These measures clearly have greater ecological and external validity than on-road evaluations and account for the strategic, tactical and operational levels. Yet neither is this choice free from problems. Car crashes are quite rare events and produce a variable with restricted range. Consequently, this parameter could have poor statistical power [24,63], even though a longer follow-up should easily compensate for this contraindication. Alternatively, the same problem could be set using a composite variable including both the number of the accidents and the number of traffic rules violations, as in the study by Pietrapiana, Tamietto et al. [61]. Finally, it should also be considered that accidents may have different causes not necessarily related to unsafe driving or individual factors. Furthermore, drivers' errors or unsafe behaviors may not always result in accidents. On the other hand, one could argue that, as these factors are distributed randomly throughout the population, they should not affect the external validity of the measure.

To summarize, three types of measures have been adopted as criterion variables for determining fitness to driving: off-road tests, on-road assessments, and the number of accidents and/or traffic rules violations after resuming driving. Off-road tests yielded very limited value in predicting driving behaviors in daily open-road situations. On-road evaluation has been used by most of the researchers assessing driving fitness. While having greater ecological validity, on-road evaluation does not address reliability and standardization, nor does it deal with the strategic level. Moreover, its external and internal validity is not clearly established. Car accident and/or traffic rules violations rate seems the most promising driving fitness measure, at least in terms of ecological and external validity, even though it involves some statistical and conceptual problems. Nonetheless, since few studies have used this measure, a comprehensive evaluation of the pros and cons is not yet available.

1.3. Injury severity

The third source of variability that makes various studies difficult to compare is the severity of the functional and cognitive impairments in patients' sample. For instance, the patients in Coleman et al.'s study [10] had sustained moderate to severe TBI, with a GCS score ranging from 3 to 12, whereas the sample tested by Korteling and Kaptein [43] had sustained extremely severe TBI with average coma duration of 33 days and high standard deviation ($SD = 51$ days). In the same vein, the 66 patients studied by Pietrapiana, Tamietto and co-authors [61] had suffered severe TBI with average coma duration of 12.43 days, even though the overall sample was more uniform than that of Korteling and Kaptein [43], having a standard deviation of 8.19 days. The involvement of more extreme cases enhances the magnitude of correlations among various measures, but further reduces the possibility of generalizing results. Indeed, Korteling and Kaptein [43] found a predictive power of coma duration and Pietrapiana et al. [61] consistently showed that the same measure significantly differed between patients that resumed driving after TBI and those who did not. Conversely, other authors (including Coleman et al. [10]) failed to address severity of injury as a potentially important predictor [25,30, 67,71].

1.4. Overlapping between the neural correlates of driving and the neural structures damaged by TBI

To our knowledge, only three recent works have studied the neural correlates of driving using neuroimaging techniques such as functional Magnetic Resonance Imaging (fMRI) or Positron Emission Tomography (PET). Walter et al. [82] tried to disentangle visuomotor from higher order cognitive functions. Their results suggest that driving engages mainly the areas concerned with perceptual-motor integration (i.e., the left sensory-motor cortex, the cerebellar regions, and the parietal cortex) and does not involve those structures associated with higher cognitive functions. According to Walter et al. [82], there might be no driving center in the brain apart from those areas involved in sensory-motor functions implicated in driving. In contrast, Uchiyama et al. [76] provided different results in a study on the neural substrates of the ability to maintain a safe distance from a preceding car. As underlined by the authors, the failure to keep a safe distance can cause rear-end collisions, which account for 30% of all traffic accidents in the USA. The driving task performed in this study activated multiple cortical and subcortical regions including the cerebellum, basal ganglia, pulvinar nuclei of the thalamus, ventral and dorsal premotor cortex, inferior parietal lobule, left primary sensory-motor cortex, supplementary motor area, and anterior cingulated cortex. Calhoun et al. [9] also reported different activations in multiple neural systems during simulated driving in a study focused on the temporal dynamics of each neural pathway involved in driving. Applying to fMRI a method derived from component analysis, the authors found six main clusters of brain areas correlated with six different cognitive domains: (1) a lower order visual domain in the occipital areas; (2) a higher order visual/motor domain in the bilateral visual associative cortex and parietal areas; (3) a visual monitoring domain bilaterally in the parieto-occipital sulcus including portions of the cuneus, precuneus, and lingual gyrus; (4) a vigilance domain in the medial frontal, parietal and posterior cingulated regions; (5) a motor control domain in the cerebellar and motor areas; (6) an error monitoring and inhibition domain in the orbitofrontal and anterior cingulated areas.

Thus, the complexity entailed in driving is evident also at the neuronal level, where multiple cerebral pathways seem to be the counterpart of various interrelated cognitive functions. Indeed, the more the concept of driving used by researchers (and related experimental tasks) becomes complex, the more neural structures associated with higher cognitive functions are found to be involved. To date, it is impossible to know whether the various samples considered in the clinical studies so far reviewed differed in the site and extent of neural structures damaged by TBI, as this data was not reported. Yet this seems possible, and even probable, considering the heterogeneous causes for TBI. Similarly, we do not know whether the extension of the overlapping between the neural correlates of driving and the neural structures damaged by TBI specifically predicts an unsafe return to driving. Clearly, this does not mean that predictions on a possible return to driving after brain injury should be based only on the site and extent of brain lesions. This would be misleading for all brain-damaged patients, in general, and for patients with TBI in particular. In fact, whereas neuroimaging techniques provide relevant information on the *involvement* of a brain area in a given task, these same methods are silent with respect to whether this structure is *necessary* for accomplishing the task [45]. This attention on which conclusions can be correctly drawn from neuroimaging data is even more remarkable for TBI patients in whom diffuse axonal injury is a cardinal neurological feature and evidence of focal lesions is frequently lacking. Notwithstanding these prudential considerations, it seems advisable for clinicians to consider, among other factors, these new neuroimaging findings in order to formulate more realistic and accurate evaluations on the actual possibility of driving after TBI. Future studies, on the other hand, should try to document as accurately as possible the site and extent of brain lesions and to test, other conditions being equal, whether different lesions are specifically associated with safe or unsafe return to driving.

1.5. Length of the follow-up

The fifth aspect that differs among studies is the length of follow-up considered, which ranges from 3 months to 1 year [4,32,41,67]. The variability of the period taken into consideration could perhaps explain why some authors reported time since injury as an important predictor [10,61] and others did not [30,71]. In TBI patients, the functional recovery is typically slow and occurs during the whole year after brain injury and sometimes beyond [33,34,55,58]. Consequently, results of studies adopting a 3 or 6-month follow-up of driving fitness after TBI do not generalize to the majority of the patients. Furthermore, those studies taking as driving fitness measures the number of post-injury accidents and/or traffic rules violations should add a further period of at least one year to the time passed between TBI and return to driving, in order to collect data about patients' behavior during actual driving in real life.

2. Conclusions

Development of reliable procedures to assess fitness to safe driving and predicting driving fitness in the real world is a crucial step in the rehabilitation process of TBI persons. However, a commonly adopted system does not yet exist, and available methods to check a patient's efficiency do not provide a sufficient guarantee of determination of the actual capabilities of driving safely. This is likely because the majority of experimental reports over the last decades have focused on the idea of predicting fitness to drive by pre-driving tests and measures bearing on rather elementary and basic functions such as perceptual-motor skills. More encouraging findings come from recent studies that have tried to consider all three levels entailed in driving properly (operational, tactical and strategic) and to adopt driving fitness measures with improved ecological and external validity. Indeed, those studies that used measures bearing on both lower- and higher-level cognitive functions and on psycho-social and personality factors often predicted a considerable amount of variability in the actual driving behavior. Still other possible predictors as anatomical site of brain lesions have not yet been adequately considered.

Identifying a common measure of fitness to safe driving which effectively assesses (and realistically approximates) each and every skill involved in actual driving in the real world and on a long-term basis is the most important next step in research and clinical rehabilitation. Indeed, the reliability and effectiveness of pre-driving predictors are assessed against the specific post-injury measure of fitness to drive adopted in a given study. A commonly shared driving fitness measure would make it possible to compare different studies and would help to make a distinction between effective and inconsistent predictors.

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Appendix 1

Research studies reviewed in the article (in alphabetic order).

Authors	Year of publication	Main focus	Key findings
Brooke et al. [4]	1992	1-2-5	Results suggested that tests of cognitive functions alone are not adequate to predict driving fitness. These tests should be used along with standardized on-road driving measures.
Calhoun et al. [9]	2002	4	Activation in the anterior cingulate cortex decreased exponentially in proportion to driving speed. Activity in cerebellum and occipital areas increased during driving but was not associated with driving speed.
Coleman et al. [10]	2002	1-2-3-5	Significant others' perceptions of the fitness to drive of the patients with TBI were the strongest predictor of patients' driving status (post-injury drivers or non-drivers) and driving frequency. Years post-injury, disability at discharge, and current neuropsychological functioning best predicted post-injury driving safety as measured by actual incidents.
Dimarco et al. [13]	2001	1-2	There was no significant change in drivin offences and skills in patients who resumed driving after TBI. The overall number of traffic accidents appears to be significantly less than it was before the TBI incidents.
Farmer et al. [17]	2000	2	The purpose of this study was to investigate the usefulness of a one-day educational injury prevention program for young people with speeding offences. The findings underscore the need to improve prevention programs and highlight the potential usefulness of existing public datasets for driving fitness evaluation.
Formisano et al. [22]	2001	1-2	Data showed that a person who suffered severe brain injury (GCS < 8) and coma lasting longer than 48 hours has a higher risk of being involved in a traffic accident.
Fox et al. [24]	1998	1-2	Closed-course, off-road driving tests are recommended for examining vehicle operation skills. A practical on-road driving test, with standardized route and driving maneuvers, is recommended for determining driving fitness.
Fox et al. [25]	1992	1-2-3	It is suggested that multidisciplinary assessment of driving competences (on-road testing included) is essential, as medical guidelines alone are insufficient to predict driving fitness.
Galski et al. [26]	1992	1-2	The authors showed that 93% of behind-the-wheel driving performance in traffic was explained cumulatively by findings from the pre-driving and simulator evaluations, as well as from behavioral and operational measures during pre-driving evaluation. Psychological tests accounted for 64% of the variance in the driving fitness measure.
Galski et al. [27]	1993	1-2	Results showed that residual deficits in cognition per se did not render a person unfit to drive and underscored the importance of considering behaviors in determining fitness. Off-road and on-road evaluation accounted for 90% and 92% of the behind-the-wheel driving fitness measure with the inclusion of behavioral data.
Galski et al. [28]	1990	1-2	The score of each pre-driving test and the overall score of the neuropsychological pre-driving evaluation did not correlate with the behind-the-wheel driving fitness measure. These findings raise serious doubts about the validity of perceptual and neuropsychological tests in assessing driving fitness.
Gouvier et al. [30]	1989	1-3-5	Results indicated that psychometric measures can be useful in predicting driving performance among drivers with disabilities. The best predictor of driving ability was the oral version of the Symbol Digit Modalities Test, which by itself accounted for 70% of the variance of the driving fitness measure.
Hawley [32]	2001	5	The existence of problems which could significantly affect driving does not prevent patients from returning to driving after TBI.
Hellawell et al. [33]	1999	5	Results illustrated the legacy of moderate head injury in influencing many aspects of everyday life, supporting the argument that the needs of patients with moderate to severe head injury should not be overlooked.
Hillier et al. [34]	1997	5	This study collected data on patients who had sustained a TBI 5 years previously. The results indicated that the subjects' living arrangements had not altered significantly, and nearly half of the patients had returned to some form of paid work. The majority (57%) felt they had improved in all areas, 19% partially improved and 8% felt they had actually deteriorated. Evidence was also provided that residual physical issues should be considered along with the more researched areas of cognition and psychosocial issues.
Jones et al. [39]	1983	1-2	Results suggested that off-road tests complement, rather than replace, on-road testing.
Katz et al. [41]	1990	5	This study sought to evaluate the ability of brain-damaged individuals to operate a motor vehicle safely at follow-up. Analysis revealed no difference between patients and control group in the type of driving, the incidence of speeding tickets, near-accidents, accidents, and the cost of vehicle damage when accidents occurred. The patient group was further divided into those who had and had not experienced driving difficulties so that initial neuropsychological testing could be compared. No significant differences were noted in any aspect of the neuropsychological test battery.

Authors	Year of publication	Main focus	Key findings
Korteling et al. [43]	1996	1-2-3	The amount of variance in the open-road driving performance that could be accounted for by both the Perceptual Speed task and the Time Estimation task was insufficient to completely replace an open-road driving fitness assessment.
Lundqvist [46]	2001	1	The study showed the complementary value of neuropsychological assessment and driving tests: the relevance of cognitive factors for interpretation of driving problems, but also the relevance of a driving test to show compensatory capacity in some drivers with brain injury.
Mazer et al. [48]	1998	1	Subjects who passed the on-road evaluation had higher average scores on the majority of perceptual tests compared with those subjects who failed. The Motor Free Visual Perception Test was the most predictive test of on-road performance. A screening process is useful in identifying persons who are not ready to undergo an on-road driving evaluation.
Meyers et al. [49]	1999	1	This study demonstrated that a short neuropsychological battery was able to tell individuals who were competent to drive from those who were not competent to drive.
Nouri et al. [54]	1987	2	This study investigated the relationship between cognitive and driving abilities after stroke. Subjects were graded into Pass, Borderline or Fail categories on the basis of the road test. A discriminant function analysis identified 10 tests which together predicted the grading of 94% of subjects into Pass or Fail categories.
Novack et al. [55]	2000	5	The authors prospectively studied individuals with TBI at fixed intervals, specifically 6 and 12 months post-injury with a window of ± one month. Results revealed significant improvements in cognitive abilities, including memory, processing speed, language abilities, and constructional skills. Although individuals with mild to moderate TBI performed better than individuals with severe TBI, both groups demonstrated equivalent rates of recovery across domains.
Olver et al. [58]	1996	5	This study examined long-term outcomes in TBI patients following discharge from a comprehensive rehabilitation program. Out of 254 TBI patients reviewed at 2 years from the injury, 103 were followed up at 5 years. Between 2 and 5 years there was increased independence. On the other hand there was a slightly higher incidence of cognitive, behavioral and emotional changes reported at 5 years. 32% of the patients working at 2 years were unemployed at 5 years. These findings suggest the need for intermittent lifelong intervention following TBI.
Pietrapiana et al. [61]	2005	1-2-3-5	Four predictors (years post-injury, accidents and traffic violations before TBI, pre-TBI risky personality index, and pre-TBI risky driving-style index) explained 72.5% of the variance in the driving fitness measure (actual post-injury accidents and traffic violations). The results suggest that to evaluate the possibility of safe driving after TBI, it would be advisable to consider carefully patients' pre-TBI histories.
Schanke et al. [68]	2000	1-2	Neuropsychological assessment of targeted functions can provide an ecological valid prediction of driving skills after brain damage. However, on-road evaluation is needed as a supplement in cases with ambiguous test findings.
Sivak et al. [71]	1981	1-2-3-5	Different tests tapping perceptual/cognitive abilities turned out to be good predictors of driving performance in persons with or without brain damage.
Stokx et al. [72]	1986	2	The results obtained in reaction-time tasks provided no conclusive evidence that severe concussion of the brain affects particular stages in information processing. Reaction-time tasks appeared to have a predictive value for the ability to drive a car.
Uchiyama et al. [76]	2003	4	The authors performed an fMRI study to determine the neural substrates of the ability to maintain a safe distance from a preceding car. The task activated multiple brain regions. Activation of the cerebellum may reflect visual feedback during smooth tracking of the preceding car. Co-activation of the basal ganglia, thalamus and premotor cortex is related to movement selection. Activation of a premotor-parietal network is related to visuo-motor coordination.
Van Zomeren et al. [79]	1988	2	In comparison with a control group matched by age and driving experience, patients with severe head injuries performed worse on driving tasks. In addition, the patient group showed clear impairments on a neuropsychological test battery. However, the only relationships found between test performance and driving behavior involved visuo-motor abilities and lateral position control. No relationship was found between the neurological status and driving skills.
Van Zomeren et al. [80]	1987	1-2	In groups of patients with acquired brain lesions about half the subjects still held a valid driving license; brain-damaged drivers could not, in general, be seen as risky drivers; and statistics show no increase in post-injury traffic violations or accidents.

Authors	Year of publication	Main focus	Key findings
Walter et al. [82]	2001	4	The authors studied healthy subjects in fMRI while they performed a driving simulator task. Activity specifically associated with driving was found only in the sensori-motor cortex and the cerebellum. It is concluded that simulated driving requires mainly perceptual-motor integration.
Wilson et al. [83]	1983	2	On public roads stroke patients exhibited special difficulties when entering and leaving motorways and handling traffic at roundabouts. On private roads, stroke patients were relatively unaware of other vehicles, exhibited difficulties in reversing, doing two things at once in an emergency and parking their car accurately on the left.

Note: The numbers reported in the Main Focus column reflect the primary investigative focus(es) of the study and correspond to the section(s) on the paper in which the cited study is discussed in more detail.