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VALIDATION OF NEUROPSYCHOLOGICAL DRIVING FITNESS TESTS FOR PERSONS WITH BRAIN DAMAGE

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Validation of neuropsychological driving fitness tests for persons with brain damage (Validatie van neuropsychologische tests voor de rijgeschiktheid van personen met hersenbeschadiging)

Drs. N.A. Kaptein en dr. J.E. Korteling
9 augustus 1994, Rapport TNO-TM 1994 A-27
TNO Technische Menskunde[1], Soesterberg

MANAGEMENT UITTREKSEL

In opdracht van het Militair Revalidatie Centrum in Doorn wordt in dit rapport de validiteit getoetst van laboratoriumtests die mogelijk de rijgeschiktheid van hersentrauma-revalidanten kunnen voorspellen.

In eerdere studies is bij gerevalideerde hersentrauma-patiënten een aantal specifieke gebreken geïdentificeerd die van belang kunnen zijn voor het uitvoeren van de rijtaak. Dit heeft geleid tot de veronderstelling dat neuropsychologische tests, geselecteerd op basis van de geconstateerde gebreken, gebruikt kunnen worden als rijgeschiktheidstest voor personen met hersenbeschadiging.

Er zijn vier tests gevalideerd: een Perceptuele Snelheid-test, de WAIS-Substitutie subtest, een Stuur-Reactie dubbeltaak en een Tijdschattingstaak. Deze taken zijn met name gevoelig voor perceptuele en aandachtstoornissen die bij hersentrauma-patiënten veelvuldig voorkomen. Naast deze laboratoriumtests werd door de Afdeling Aanpassingen van het Centraal Bureau Rijvaardigheidsbewijzen (CBR) een rijgeschiktheidstest op de openbare weg afgenomen.

De resultaten lieten zien dat bij mensen met hersenbeschadiging prestaties op zowel de perceptuele snelheid-taak als de tijdschattingstaak significant zijn gecorreleerd met de rijprestatie. Door het combineren van verschillende tests (en rekening houdend met comaduur en rijervaring) kon 35.3% van de variantie in de prestatie op de rijgeschiktheidstest op de openbare weg worden voorspeld. Echter, zelfs als de testresultaten werden gecombineerd, kon de rijprestatie niet zodanig worden voorspeld dat het gerechtvaardigd zou zijn de rijtest op de weg, die nu door het CBR wordt gebruikt, te vervangen door één of meer van de laboratoriumtaken.

Geconcludeerd wordt dat andere tests ontwikkeld dienen te worden. Aanbevolen wordt te onderzoeken of (low-cost) rijsimulatoren hierbij een functie kunnen vervullen.

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[1] Per 1 februari 1994 is de naam Instituut voor Zintuigfysiologie TNO gewijzigd in TNO Technische Menskunde.

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SUMMARY

The present study validates four simple neuropsychological tests as tools to assess the driving fitness of brain-damaged patients, i.e., a Perceptual Speed test, the WAIS Symbol-Digit Substitution subtest, a Tracking-Reaction dual task and a Time Estimation task. These tasks focus on perceptual and attentional deficiencies that most brain-damaged patients show. Subjects performed both the laboratory tests and an on-road driving test. The results indicated that, for brain-damaged subjects, performance on both the Perceptual Speed task and the Time Estimation task were significantly correlated with driving performance. Neither of the tests, however, predicted on-road driving to a degree that would justify replacing the on-road driving test that is currently used to assess the driving fitness of brain-damaged patients. When combined with coma duration and driving experience, the Perceptual Speed and Tracking-Reaction tests together could explain 35.3% of the variance in on-road driving performance. More detailed analyses showed that also a combination of these test scores did not provide enough justification to replace on-road driving fitness assessment. All in all, assessing driving fitness of brain-injured persons with the to-be-validated laboratory tests was not justified by the present results. As a consequence alternative tests (e.g., using low-cost driving simulators) need to be developed.

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Validation of neuropsychological driving fitness tests for persons with brain damage

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SUMMARY

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TNO Technische Menskunde[1]
Soesterberg

Validatie van neuropsychologische tests voor de rijgeschiktheid van personen met hersenbeschadiging

N.A. Kaptein en J.E. Korteling

SAMENVATTING

In opdracht van het Militair Revalidatie Centrum in Doorn wordt in dit rapport de validiteit getoetst van laboratoriumtests die mogelijk de rijgeschiktheid van hersentrauma-revalidanten zouden kunnen voorspellen. Er zijn vier tests gevalideerd: een Perceptuele Snelheid-test, de WAIS-Substitutie subtest, een Stuur-Reactie dubbeltaak en een Tijdschattingstaak. Deze taken zijn met name gevoelig voor perceptuele en aandachtstoornissen die bij hersentrauma-patiënten veelvuldig voorkomen. Naast deze laboratoriumtests werd door de Afdeling Aanpassingen van het Centraal Bureau Rijvaardigheidsbewijzen (CBR) een rijgeschiktheidstest op de openbare weg afgenomen. De resultaten lieten zien dat bij mensen met hersenbeschadiging prestaties op zowel de perceptuele snelheidstaak als de tijdschattingstaak significant zijn gecorreleerd met de rijprestatie. Echter, geen van de tests kon de rijprestatie zodanig voorspellen dat het gerechtvaardigd zou zijn de rijtest op de weg, die nu door het CBR wordt gebruikt, te vervangen door één van de laboratoriumtaken. Er zullen andere tests ontwikkeld dienen te worden (bv. met behulp van low-cost rijsimulatoren).

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1 INTRODUCTION

In modern society, the possibility to drive a car is of considerable importance for the quality of life. As a consequence, after rehabilitation from severe head injuries a key question is whether or not patients have recovered to a degree that allows them to start or recommence car driving. After recovery, the majority of head-injured patients starts to participate in traffic without seriously considering the consequences (Brouwer & Van Zomeren, 1992). Only after severe traumatic injury it is as a rule questioned whether the patient is able to drive a car. The serious risk at long-lasting effects of severe head injuries implies that the driving fitness of brain-damaged patients should be carefully assessed. From the perspective of traffic safety, unsafe drivers should be timely identified and be denied a driving license. On the other hand, since not being able to drive a car has such overwhelming personal implications, it is not desirable either to erroneously prohibit people from driving a car. Consequently, the assessment of driving fitness requires reliable and valid assessment techniques.

In cooperation with the Dutch Military Rehabilitation Center (MRC), at the TNO Human Factors Research Institute, a number of studies have focussed on the identification and assessment of specific perceptual and cognitive deficiencies that result from traumatic brain injuries (see Ravestein et al., 1982; Gaillard et al., 1984; Stokx, 1984; Korteling, 1987). In the present study four simple neuropsychological tests are validated as tools to assess the driving fitness of brain-damaged patients.

1.1 Previous research

When reviewing the literature on neuropsychological driving-fitness tests, at first sight the results of the various studies appear to be highly incompatible. Whereas some of the studies reported a predictive power[2] of only about 0.20 to 0.25, other studies (Galski et al., 1992; Korteling, 1990; Sivak et al., 1981) came up with more favorable results, with a predictive power of up to 0.94. In the following sections these differences in results will be investigated in more detail.

In their 1981 study, Sivak et al. investigated the effects of brain damage on perceptual or cognitive skills and on driving. Subjects performed a battery of laboratory tests followed by driving tasks in a controlled environment and actual in-traffic driving. The in-traffic task consisted of driving a fixed 17 km trajectory of various road types. Performance was evaluated on 144 points along the route as 'well executed' or 'not well executed' on five different aspects of performance: gap acceptance, limit line (stopping line), observation, path and speed. A

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[2] The 'predictive power' of one or more predictor variables for a criterion variable refers to the proportion of variance of the criterion variable that can be explained by predictor variables, i.e. the square of the (multiple) correlation coefficient.

Composite Driving Index (CDI) was derived that summarized the various judgments in order to quantify performance. For brain-injured subjects, the CDI correlated strongest (from the laboratory tasks) with Picture Completion ($r=0.72$; $r^2=0.52$), Picture Arrangement ($r=0.46$; $r^2=0.21$) and Stereo Depth ($r=0.52$; $r^2=0.27$). No significant correlation of the CDI with any of the closed-course tasks was found. Controlling for the results of some of the laboratory tests eliminated the difference in driving performance between able-bodied and brain-damaged persons. On the other hand, none of the closed-course measures correlated significantly with open-road driving. Subjective overall ratings of driving performance (by a different observer) correlated strongly with the CDI (between $r=0.74$ and $r=0.83$; r^2 between 0.55 and 0.69). Different tests were predictive in case of normal drivers compared to brain-damaged drivers, suggesting that different skills were critical for driving performance in these groups. These results would suggest that neuropsychological tests might be used to predict driving performance to a considerable degree. Yet, Sivak et al. (1981) did not transform their findings into a pass-or-fail decision system, so that no data are available on the amount of misses and false alarms of such a system. No multiple correlation coefficients were calculated either.

Galski et al. (1992) more or less extended on the method of Sivak et al. (1981). They also used a highly controlled and standardized on-road evaluation method as their criterion variable. As predictors they used a combination of laboratory tests, driving simulator tests, and off-road driving performance measures. Their result was impressive: a predictive power (proportion explained variance) of 0.93. Even when only laboratory tests were used as predictors a predictive power of 0.64 was obtained.

In contrast with the findings of Sivak (1981) and Galski et al. (1992), Fox et al. (1992; 1993) reported a failure to reliably predict on-road driving performance (rated as 'fail', 'borderline' or 'pass' by an examiner) from medical or neurological pretests. Moreover, they found low internal consistency of the subjective on-road performance ratings when validated against objective driving performance measures.

Korteling (1990) obtained several high correlations of up to $r = 0.94$ ($r^2 = 0.88$) between performance on a duration-estimation task and a closed-course driving task. The driving task consisted of following a lead-vehicle while keeping the inter-car distance at a constant level of 15 m as accurately as possible with minimal delay or braking at the onset of the brake lights of the lead-vehicle. Performance on this criterion task only reflects speed-related variables of actual on-road driving capabilities. Hence, one may suppose that correlations among laboratory RT tasks and speed-related driving elements typically will be high. This, however, was not the case. Correlations related to other laboratory measures and correlations between duration estimation and driving performance were low for a group of older subjects and the control group included in this study. Therefore, even within this restricted domain of human performance correlations among laboratory and driving indices are not necessarily high.

Most of the research so far has focussed on the problems related to attentional and perceptual-motor capacities. Since these tests alone have not yielded the desired results, some researchers have addressed cognitive and personality aspects. Van Wolffelaar et al. (1988) investigated whether predicting driving performance of brain damaged persons should be based on the assessment of higher cognitive skills like planning, programming and evaluation of goal-directed behavior rather than on perceptual-motor skills. They found no significant predictive value of tasks that require these cognitive skills and even failed to obtain differences in performance on these tasks between able-bodied and brain-injured persons. Brouwer et al. (1992) recognized that social responsibility may be an additional factor of importance. Rehabilitated persons that are sufficiently aware of their limitations, and compensate for that in their behavioral decisions may be safe drivers, despite their limitations. On the other hand, small deficiencies may have severe consequences if a driver does not recognize his or her decreased driving fitness. Brouwer et al. (1992) concluded that on-road assessment is an indispensable tool for assessing fitness to drive.

It is evident that different approaches have been used which, probably, has led to the incompatibility in results. On two major aspects the various approaches are different: the type of criterion variables and the type of predictors that were used. As criterion variables mostly on-road tests were used. Some researchers have had experienced driving examiners rate subjects' driving performance, either as an overall judgment or differentially for different aspects of the driving task. Other researchers (Sivak et al., 1981; Galski et al., 1992) have formalized the on-road driving assessment by explicitly defining the specific aspects of driving that had to be rated on the different parts of the test course. If only reliability and experimental control are considered, the latter approach is superior. Yet, as regards the external validity of the criterion variable, the unformalized on-road procedure might have to be preferred. A possible problem with formalized assessment procedures is that cognitive and strategical aspects of driving may not be taken sufficiently into account. It is conceivable that, when assessing overall driving performance, examiners, on the other hand, do take these aspects into consideration. Also, the structured type of on-road driving assessment might be evaluating maximum sub-task performance rather than overall driving behavior. Though any testing procedure is based on the assumption that test performance is predictive for behavior in reality, maximum performance on one isolated aspect of the skill that is to be assessed may not be very predictive for the variable of interest: fitness to drive in real traffic.

The second aspect in which the various studies are obviously different is the type of predictive tests that were used. All studies used laboratory tests, i.e. neuropsychological tests assessing some basic skills that may be relevant to the driving task, and that have been observed to be affected in brain-injured persons.

In addition, some studies use simulator and off-road driving performance as predictors as well. On the predictive power of off-road testing for on-road driving capacity contradicting results have been obtained. Galski et al. (1992) were able to account for 64% of the variance in their criterion variable by off-road driving performance (the same amount as could be explained by laboratory task performances), whereas Sivak et al. (1981) did not even find significant correlations between closed-course and open-road driving. Note also that as regards off-road driving performance the choice of driving tasks is very different between studies, and is likely to be related to, on the one hand, the predictability of off-road driving performance from laboratory test scores and, on the other hand, the predictability of on-road driving performance from off-road driving performance measures (see, e.g., Galski et al., 1992; Korteling, 1990; and Sivak et al., 1981). In theory, off-road driving performance might predict driving fitness to a considerable degree. The validity of this method might depend on the selected driving tasks.

1.2 The present study

The goal of the present study is to extend on these studies in order to assess the power of a number of laboratory tests to predict driving fitness. First, on the basis of the relevant literature, a selection was made of a small battery of laboratory tests of which the results may be expected to predict the driving capability of brain-injured patients. Second, the on-road driving performance of stably rehabilitated brain-damaged persons was assessed by the Dutch Driving Licensing Agency (CBR). Third, these subjects were tested with the selected laboratory tests, so that the predictive power of these laboratory tests for driving fitness could be quantified.

Car driving has been viewed as a complex skill consisting of a number of basically independent components (e.g., Duncan, 1990). This may suggest that assessing performance on component skills would be sufficient to predict driving performance. However, apart from basic perceptual-motor skills, higher-level strategies and risk-taking behavior are of crucial importance to the driving task. Therefore, attempts to develop predictive laboratory tests for driving performance of *normal* subjects that do not take these factors into account may be doomed to fail. On the other hand, severely brain-injured people share a number of deficiencies that may have specific implications for basic abilities involved in the driving task. Therefore, for patients with traumatic brain-injury the use of predictive tests may be expected to be more successful.

In order to select adequate tests, potential driving problems are derived from the dysfunctions that characterize brain-injured patients. Neuropsychological tests are then selected for quantification of the severity of these dysfunctions, and an on-road driving test is performed to investigate the relation between driving problems and the degree of dysfunction.

A large amount of research has been devoted to the identification of the long-term deficiencies that may result from severe brain damage (see Fox et al., 1992; Van Zomeren et al., 1987; Van Wolffelaar et al., 1988 and Brouwer et al., 1992 for discussions). Evidently, traumatical brain injuries all are to a certain extent unique. Nevertheless, a number of frequently observed characteristics can be identified, distinguishing attentional, temporal, personality and motor deficiencies.

Attentional deficiencies

The unpredictability of the behavior of other road users implies that automobile drivers continuously need to detect changes in the traffic environment in order to be able to react appropriately. As a consequence, attentional deficiencies may be assumed to be highly relevant to a patient's driving fitness. Attentional deficiencies of brain-damaged persons are generally observed as Divided Attention Deficits (DADs) rather than as Focussed Attention Deficits (FADs, see Deelman et al., 1980; for the distinction see Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977). An FAD entails the incapacity to concentrate on one source of information that is embedded in a context of other sources of information (e.g., on the behavior of a lead-vehicle), whereas a DAD involves the disability to simultaneously pay attention to various sources of information (e.g., monitoring several cars at a time).

The two types of attentional deficiencies can be assessed with different tests. FADs should, for instance, show up in performance on a Stroop-task (Stroop, 1935; MacLeod, 1991). DADs particularly show up in tasks that are characterized by extreme time pressure. In such a type of laboratory task, brain-injured subjects have proven to be more sensitive to the speed of stimulus presentation compared to normal subjects (Gronwall & Sampson, 1974). Therefore, DAD tests might be predictive for driving fitness of brain-injured persons.

Temporal deficiencies

When driving a car in busy traffic, it is important to timely react to unexpected changes in the demands of the driving task, for instance when suddenly stumbling upon a traffic jam. A minimum basic speed of information processing might be required in order to drive safely. Unfortunately, an overall slowness of information processing has been observed in virtually all brain-damaged patients (e.g., Ravestein et al., 1982). In addition, Deelman et al. (1980) suggested that observed attentional and memory deficiencies are due to the general slowing of specific information processing stages (see also Stokx & Gaillard, 1986). In either case, the response to sudden events in the traffic environment that require an immediate action might come late. Simple reaction time tests, quantifying a person's general (or stage-specific) information processing speed, might be predictive for problems of this sort when participating in traffic.

Personality deficiencies

Brain-damaged persons sometimes show apathy, lability, irritability, lack of self-criticism or an egocentric attitude (Saan & Van Zomeren, 1981), possibly resulting in increased impulsivity or risk-taking behavior in traffic. Note that the direction of the causality in the relationship between brain-damage and personality characteristics is unclear, since drivers that, for example, tend to take risk in the first place may be more vulnerable in traffic and therefore have an increased probability to suffer from traumatic head injuries (see also Brouwer et al., 1992). Traffic safety is not necessarily only affected by the quality of a person's information processing (that was discussed above), since drivers that are aware of their inferior performance may compensate for that by choosing adaptive driving strategies. For instance, they might choose not to overtake another vehicle, or, when they do overtake, use larger safety margins. On the other hand, brain-damaged patients that have lost the ability to compensate for their inferior performance are likely to be unsafe drivers.

Motor deficiencies

A different source of problems may stem from motor deficiencies of brain-injured persons. To the extent that brain-damage causes peripheral motor dysfunctions or moderately impaired motor control, vehicle adaptation mostly suffices to guarantee safe in-traffic behavior (Ravestein et al., 1982). More general and severe deficiencies in motor control may make a patient unfit to drive a vehicle. Especially the perceptual-motor coordination might be crucial for driving, since in a rapidly changing traffic environment the occasional occurrence of critical situations suddenly forces drivers to act in response to visually perceived events.

A number of clear and measurable problems of brain-injured persons that potentially cause driving problems have been identified. If the subset of brain-damaged persons that are unfit to drive a vehicle share underlying deficiencies, then assessing these deficiencies might help to predict driving performance. Therefore, the deficiencies discussed above can be used to design and select tests that predict whether or not individual stably recovered brain-injured persons are fit to drive a vehicle.

In the present study, tests for personality and motor deficiencies are not taken into account. The four tests that are validated were primarily selected with regard to attentional (Time Estimation, Tracking-Reaction) perceptual (Perceptual Speed) and perceptual-motor abilities (WAIS Symbol-Digit Substitution, Tracking-Reaction), since these kinds of abilities are generally accepted to be particularly vital to automobile driving.

2 METHOD

2.1 Subjects

Thirty-eight subjects participated in this experiment. All had recovered to a stabilized level from traumatic brain injuries. All subjects had been in the possession of their driving license at the time that they were injured.

The subjects were 5 women and 33 men. They had a mean reported driving experience of 109.2 km (SD = 86.3 km). Average coma duration was 33 days (SD = 51 days). They were tested at least 1 year after the accident. All subjects had normal or corrected-to-normal vision. Ages at the time of the injury were between 17 and 55 years (mean: 29.8; SD: 10.9).

2.2 Driving Test

Driving capacity of subjects was tested by the Division of Adaptations of the CBR. The test consisted of the standardized testing procedure of the Adaptation Department. It consisted of (relatively unstructured) on-road driving and lasted approximately 30 to 50 minutes. It took place in a rather busy urban traffic environment. Twenty-three out of thirty-eight subjects performed the driving test in a car that was equipped with an automatic gear. All subjects used their own cars on the driving test.

Experts on car-adaptations and driving fitness assessment judged the subjects' driving performance on five dimensions that were subdivided into a number of elementary driving aspects (see Table I). These dimensions were: temporal aspects, attentional aspects, flexibility, technical driving and traffic rules. On several aspects of each dimension the examiner rated performance (on a scale ranging from 2 to 9). Within categories ratings were averaged over the various aspects.

Table I Survey of categories and aspects of driving behavior that were used to rate driving performance on the on-road driving test.

category	aspects to be judged
temporal aspects	driving speed is high enough slows down adequately timely announcement of actions timely observation and judgment of other traffic reacting fast to observations fluent execution of maneuvers
attentional aspects	appropriate mirror usage dead angle taken into account did not hinder other traffic good judgment of traffic situations selective attention to relevant information adequate distribution of attention among driving tasks
flexibility	appropriate order of actions right choice of gear (if no automatic gear) keeping the right distance behavior adaptation interaction with other drivers lane position
technical driving	control of the steering wheel pedal control change of gear fluency of driving
traffic rules	obedience of traffic rules

2.3 Laboratory Tests

Driving fitness prediction was assessed for four laboratory tests: Perceptual Speed, Symbol-Digit Substitution, Time Estimation and Tracking-Reaction.

2.3.1 *Perceptual Speed (PS)*

Perceptual speed, defined as the speed in matching symbolic figures, has been assumed to reflect a basic perceptual ability (see Caroll, 1993 for an overview). The present perceptual speed test was a paper-and-pencil test (Kema, 1972). On each trial subjects had to indicate which two out of four symbolic figures were identical. See Fig. 1 for an example of a stimulus. The correct response in case of this example would be "AD". Responses had to be given vocally.

In three minutes subjects had to respond to as many trials as possible. The test score was defined as [n correct trials – (0.20 × n errors)]. The score on the Perceptual Speed task will be referred to as PS.

had been green for less than 3000 ms the subject had to press the left button (with the index finger). If that period was longer than 3000 ms, the right button had to be pressed (with the middle finger). The duration that the bottom square was green was chosen randomly out of four intervals between 2250 and 3750 ms (2250, 2750, 3250, 3750 ms). Feedback after incorrect or slow responses (after more than 2000 ms) was given by means of a brief 1000 Hz tone. As test scores are used: error percentage and mean RT, which will be referred to as TE-err and TE-rt, respectively. Stimulus presentation and data collection were governed by an ATARI 1040 ST computer with an ATARI SC1224 color monitor. Each of the four different yellow-time durations was presented 15 times, resulting in one session of 60 stimulus presentations.

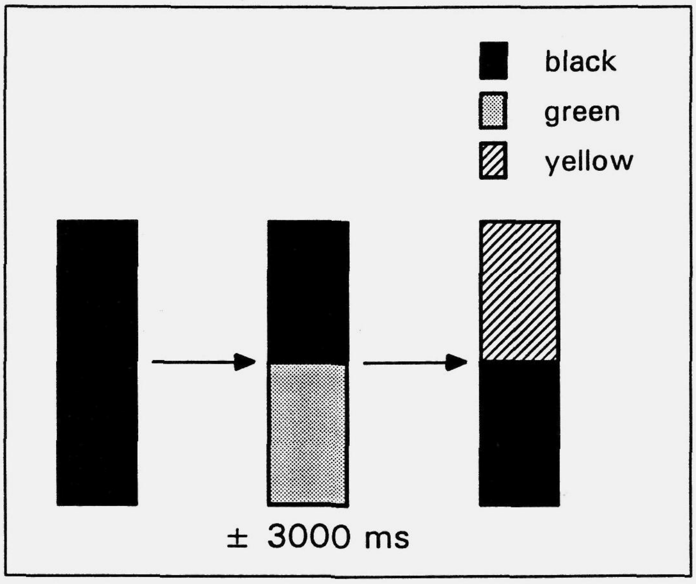

Fig. 3 Example of trial events in the Time Estimation task. Subjects judged whether the bottom square was green for durations shorter or longer than 3000 ms.

2.3.4 *Tracking-Reaction (TR)*

The Tracking-Reaction task was a dual task, that consisted of a compensatory tracking task and a 2-Alternative Forced Choice reaction task.

In the tracking task (see Fig. 4) a laterally moving target (a picture of a car seen in bird's eye view) had to be kept in the middle of the right lane (plotted on a PC monitor) by controlling a mouse with the preferred hand. The target's lateral movement was determine by a band-limited random signal (>1Hz).

Fig. 1 The Perceptual Speed Task. Subjects had to indicate which two out of four symbols were identical. In this example the correct response would be "AD".

2.3.2 *Symbol-Digit Substitution (SDS)*

The Symbol-Digit Substitution Test of the Wechsler Adult Intelligence Scale (Wechsler, 1981; see Stinissen et al., 1970 for the Dutch translation that was actually used) was a paper-and-pencil test. Subjects were provided with a decoding key, that indicated for each of nine symbols which of the numbers 1 to 9 it replaced (see Fig. 2). Subsequently a long list of symbols was presented. Subjects had to decode the symbols, and write down the corresponding numbers. The task was to decode as many symbols as possible within 90 s. The test score was defined as the number of correct trials. Trials that were completed out of sequence were not counted. Test scores were not corrected for age or gender. The score on the Symbol-Digit task will be referred to as SDS.

Fig. 2 The WAIS Symbol-Digit Substitution Test. The figure shows the decoding key. Subjects were presented with a long list of symbols, and had to decode as many symbols as possible.

2.3.3 *Time Estimation (TE)*

The Time Estimation task was adopted from a study of Korteling (1990) that showed that RTs as well as error rates of this test predicted performance of brain-damaged subjects on speed-related driving tasks (e.g., braking on seeing the brake lights of a lead-car) conducted on a closed circuit.

The test was designed to mimic the estimation of the yellow-time of a traffic light. Two black squares were presented on top of each other on a video screen (see Fig. 3). At the start of each trial the bottom square turned green. After a period of between 750 and 5250 ms, the green square turned black again and, at the same time, the top square turned yellow. At that moment the subject was required to press one of two response buttons of a mouse. If the bottom square

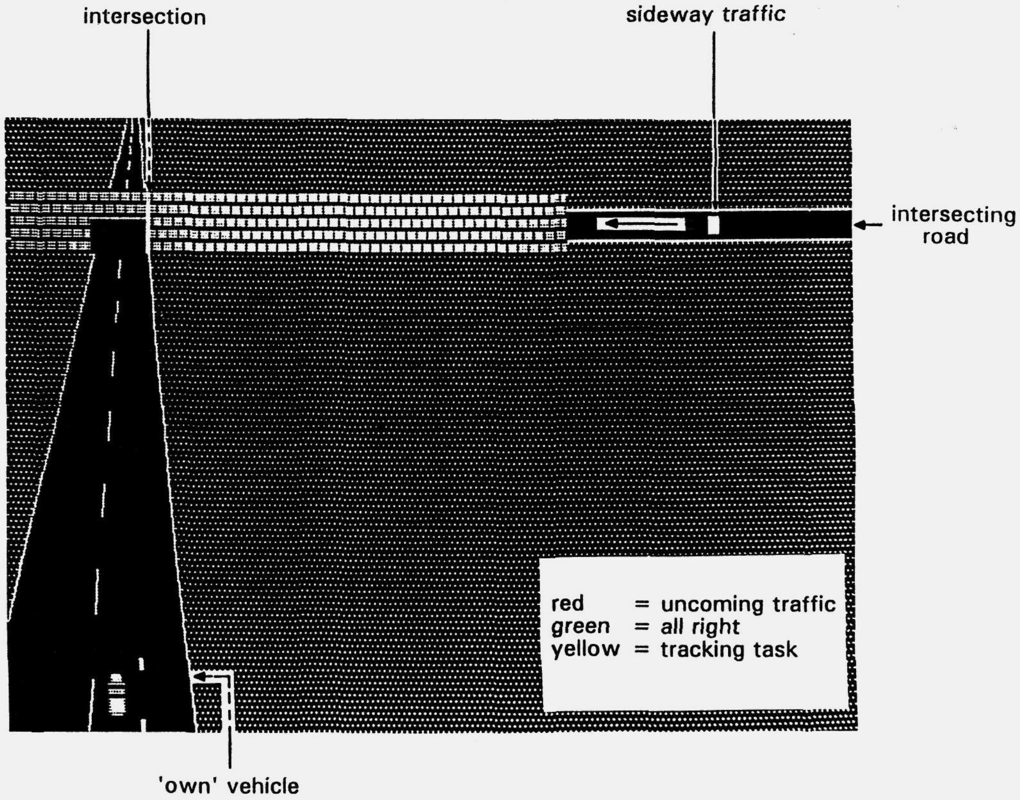

Fig. 4 The Tracking-Reaction task. The ’own’ vehicle had to be kept in the middle of the right lane by controlling a mouse, while the position of sideways traffic had to be monitored. Subjects responded whether the sideways traffic had reached the intersection.

The reaction task, performed concurrently with the tracking task, consisted of reacting as fast and accurately as possible to a square dot (simulating a car) that was moving from right to left over a straight intersecting road. The intersecting stimulus moved with a constant speed and did not change course. The stimulus remained visible until it disappeared behind a wall. A trial ended as soon as the car had reached its target position. The target position could be one out of four possible positions: at two different distances, both before and after the intersection. When the car had reached its target position a beep was given (880 Hz, 0.1 s). After the beep subjects had to respond as fast as possible whether or not the approaching car (masked by the wall) had crossed the intersection. If subjects judged that it had, they were respond by pressing the left button of the mouse; if not, the right button had to be pressed. Subsequently, 200 ms after the response, the actual position of the approaching car was shown to the subject for 1 s. Subjects were informed by means of a 520 Hz beep when committing an error. After an idle period (chosen randomly between 250 and 1750 ms), the next trial started and a new stimulus appeared on the monitor screen. Stimuli could move at three different speeds. Each possible combination of stimulus properties was presented five times, yielding 3 (speed levels) × 4 (target positions) × 5 (replicas) = 60 stimulus presentations.

Subjects were instructed to divide their attention equally among both tasks. They received feedback on their strategy of attention allocation by means of the color of their own car, telling them whether they should pay more attention to either of the subtasks[3]. During the entire test, an explanation of the meaning of possible colors was projected in a corner of the monitor (green: all right; red: pay more attention to the oncoming traffic; yellow: pay more attention to the tracking task).

As test scores were defined: tracking performance (on the tracking task), percentage of errors and mean RT (both on the sideways traffic task), which will be referred to as TR-tr, TR-err and TR-rt, respectively. Also the division of attention was quantified as a ratio score (TR-rat), that might be sensitive to Divided Attention Deficiencies.

Stimulus presentation and data collection were governed by an ATARI 1040 ST computer with an ATARI SC1224 color monitor.

2.4 Procedure

All subjects were tested separately. The on-road driving test always preceded the laboratory tests. If subjects failed the driving test, usually a number of additional lessons were taken before re-examination. Only the first driving test of each subject was included in the analyses.

The laboratory tasks were carried out in one session of almost two hours per subject. All subjects started with the Time Estimation task (to begin with one practice session of 60 trials), followed by the Symbol-Digit and Perceptual Speed tasks (both without practice) and finally the Tracking-Reaction task (preceded by one practice session of 60 trials).

3 RESULTS

3.1 Correlations among driving measures

The Appendix gives the results (means and standard deviations over subjects) of both the driving task and the laboratory tests. Table II shows the correlations (Pearson-r) between the driving performance ratings on different dimensions[4].

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[3] The allocation of attention was monitored by means of the ratio of performance on the two subtasks. The allowed range for this ratio was determined by means of a pilot experiment. In that pilot experiment 10 subjects were instructed to divide their attention among the subtasks in five possible ways: 100%-0%, 75%-25%, 50%-50%, 25%-75% and 0%-100%.

[4] In all Tables only results are printed that were statistically significant with $p<0.05$.

Although the examiners were clearly instructed to independently judge the drivers on the different dimensions of driving, the measures were highly correlated, indicating that either the raters were not able to separately judge performance on each dimension or that performances on the various driving dimensions are related. In either case it is not meaningful to consider the dimensions separately in the present analysis. An overall driving performance measure was obtained by averaging the different driving performance ratings for each subject. If not specifically indicated otherwise, further analysis is based on this overall driving performance measure.

Table II Correlations between driving task ratings (correlations with | R | > 0.271 are significant at $p<0.05$).

(n=38)	flex	obs	rules	techn	temp	overall
flex	1					
obs	0.893	1				
rules	0.834	0.876	1			
techn	0.868	0.816	0.784	1		
temp	0.932	0.900	0.852	0.877	1	
overall	0.958	0.951	0.923	0.918	0.967	1

3.2 Predictive power of individual laboratory tests

In order to evaluate the predictive power of the laboratory tests for driving fitness, correlations of test variables with the criterion variable was calculated, i.e., with the overall driving performance measure (see Table III).

Table III Correlations of test variables with the driving performance measure. These correlations are significant ($p<0.05$) for | r | > 0.271.

(n=38)	driving performance
PS	.281
SDS	n.s.
TR-tr	n.s.
TR-err	n.s.
TR-rat	n.s.
TR-rt	n.s.
TE-err	-.287
TE-rt	n.s.

Most correlations were not significant. The data shown in Table III suggest that Perceptual Speed and Time Estimation (error score: err) were the most promising predictors. However, even with these predictors correlations, if significant, were generally low.

None of the correlations between independent variables and the criterion variable was significant. A logical next step is to combine test variables and independent variables and to calculate multiple correlation coefficients[5]. See Table IV for these multiple correlations with driving performance, the various laboratory task measures and either coma duration (that was transformed in logarithmic form) or driving experience, or both. Taking other independent variables (age, type of gear, number of additional driving lessons) into account did not significantly increase predictive power.

Table IV Multiple correlations of test variables with the driving performance measure, driving experience and coma duration. Correlations are significant for $|R| > 0.397$, $|R| > 0.450$, $|R| > 0.494$. $|R| > 0.531$ and $|R| > 0.564$ with 2, 3, 4, 5 and 6 predicting variables, respectively.

(n=38)	driving experience	ln coma	ln coma and driving exp.
PS	0.446	n.s.	n.s.
SDS	n.s.	n.s.	n.s.
TR-tr	n.s.	n.s.	n.s.
TR-err	n.s.	n.s.	n.s.
TR-rt	n.s.	0.430	n.s.
TR-rat	n.s.	n.s.	n.s.
TR-all	n.s.	n.s.	n.s.
TE-err	n.s.	n.s.	n.s.
TE-rt	n.s.	n.s.	n.s.
TE-all	n.s.	n.s.	n.s.

Table IV shows that, when corrected for, respectively, coma duration and driving experience, only PS and TR-rt significantly predicted driving performance. Most promising was Perceptual Speed with driving performance ($r = 0.47$, which means that 19.9% of variance in driving performance was accounted for). Tracking-Reaction-rt together with coma duration produced $r = 0.43$ (18.5% of variance in driving performance explained. Thus both PS and TR-rt yielded significant predictions, but only explained a small part of variance.

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[5] Multiple correlation coefficients in this study are not corrected for shrinkage. Shrinkage refers to the phenomenon that multiple correlation coefficients that are based on within-sample correlations tend to overestimate the overall correlation between predictors (i.e., the laboratory test scores) and criterion variable (i.e., rated driving performance) in a population (e.g., Ferguson, 1971).

3.3 Predictive power of a combination of tests

Although the laboratory tests were primarily designed to be used as stand-alones, the present set-up made it possible to combine the results through multiple regression analysis. This may increase the amount of explained variance. The results presented in § 3.2 show that incorporating driving experience and coma duration into the analyses might increase predictive power. Since these variables reflect properties of the particular sample of subjects that was used, and since measuring these variables goes without additional effort, from a practical point of view it seems reasonable to include driving experience a priori into the regression equation that will be deduced.

Table V shows the multiple correlations obtained with pairwise combinations of measures. Each entry of Table V denotes the multiple correlation of overall driving performance with driving experience, coma duration (natural logarithm, ln[x], of the number of days patients had been in coma) and the two respective laboratory measures.

Table V Multiple correlations of pairs of predictor variables, driving experience, coma duration and driving performance measures (correlations are significant for | R | > 0.494).

(n=38)	PS	SDS	TR-tr	TR-err	TR-rt	TR-rat	TE-err	TE-rt
PS	1							
SDS	n.s.	1						
TR-tr	n.s.	n.s.	1					
TR-err	n.s.	n.s.	n.s.	1				
TR-rt	.594	.569	.499	.569	1			
TR-rat	n.s.	n.s.	n.s.	n.s.	n.s.	1		
TE-err	n.s.	n.s.	n.s.	n.s.	.513	n.s.	1	
TE-rt	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	1

Table V shows that the highest correlations were obtained when, apart from driving experience and coma duration, Tracking-Reaction-rt was included. The highest correlation was obtained with TR-rt and Perceptual Speed ($r = 0.59$).

Adding other variables did not significantly increase any of the correlations. Therefore only the predictors driving experience, coma duration, PS and TR-rt were included in the regression equation. Driving experience and coma duration in combination with performance on the Perceptual Speed task and the Tracking-Reaction Task (TR-rt) accounted for 35.3% of variance in rated driving performance.

It could be argued that, rather than to calculate correlation coefficients, the utility of predicting driving fitness from laboratory test scores should be assessed in terms of passing or failing a driving test. The actual variables of interest are the predicted and observed probabilities that fit and unfit drivers were correctly identified. Accordingly predicted driving performance was compared with actual rated driving performance. On the basis of their individual laboratory test scores it was predicted by means of a regression analysis whether patients would be fit to drive a vehicle. The following regression equation (1) was used:

$$z_{dr.perf.} = .233 * z_{dr.exp.} -.377 * z_{coma} + .448 * z_{PS} + .518 * z_{TR\text{-}rt} \qquad (1)$$

Table VI shows that 64% of the unfit drivers would fail and 80% of the fit drivers would pass the test. This means that 46% of *unfit* drivers is predicted to pass, whereas 20% of *fit* drivers is predicted to fail the test. Although by means of a criterion shift these proportions could be balanced, it is clear that these proportions of incorrect predictions are not acceptable if the test were considered to be the only criterion for fitness to drive.

Table VI Comparison of predicted and observed performance on the on-road driving task. The predictions were calculated by means of the following regression equation: $z_{dr.perf.} = .233 * z_{dr.exp.} - 0.377 * z_{ln(coma)} + .448 * z_{PS} + .518 * z_{TR\text{-}rt}$.

		observed	
	(n=38)	< 6	≥ 6
predicted	< 6	7 correct rejections	5 misses
	≥ 6	6 false alarms	20 hits

A final purpose of testing brain-damaged patients might be to identify a small group of patients that are extremely likely to fail the driving test. This is possible if, for example, the worst 10% of subjects as regards performance on one or more of the laboratory tests would have collectively failed the driving test. No such result was found, however. Note that all subjects in the present study did a driving test. Subjects that were judged not to be able to do the driving test were not tested in the laboratory either. Moreover, part of the patients with severe deficiencies, that would be identified by neuropsychological tests, might not even consider to recommence car driving.

4 DISCUSSION

In the present study four laboratory driving-fitness tests for brain-injured patients have been validated. Results showed that the results of the Perceptual Speed test (PS) and the Time Estimation task (the error score: TE-err) significantly predicted driving performance, although the predictive power of these tests was insufficient to permit replacing on-road driving fitness tests by one of the laboratory tests. Driving-fitness predictions were improved by combining scores on several tasks. In the present study, 35.3% of the variability in rated driving performance was accounted for by the combination of the results on two laboratory test (Perceptual Speed and Tracking-Reaction-rt) together with coma duration and reported driving experience. The resulting regression equation was used to compare predicted and observed on-road driving performance. The results did not support the option to exclusively use the predictor tests to assess driving fitness of brain-injured patients.

The present results suggest that other tests than the ones that were assessed need to be developed for predicting the fitness to drive of brain-damaged patients. A possibility is to use driving simulators. Simulator driving is likely to require the greater part of the basic skills that are used for on-road driving. In addition, structured and controlled performance measurement under predefined critical conditions is relatively easy. For instance, Galski et al. (1992) found driving simulator performance to be predictive for on-road performance (R^2 = 0.63). Further research will be needed to evaluate driving simulators as a tool for testing driving fitness.

Other groups of drivers than brain-damaged patients may also benefit from a test that evaluates driving fitness. For example, it may be desirable to be able to test the driving fitness of older drivers. An advantage of a (low-cost) simulator driving test over predictive laboratory tests might be that its validity does not depend strongly on assumptions on underlying deficiencies that are unique to a small group of people. As a consequence, it may be feasible to develop a standard testing procedure that is predictive of driving fitness and that can be used both for older drivers and for drivers that have suffered from a variety of injuries. In that case testing costs may remain relatively low.

A final note should be made on the general idea of predicting driving performance of brain-injured patients. It has been shown (Sivak et al., 1981) that driving performance of brain-injured compared with normal subjects is predicted by different neuropsychological tests. Since the degree and nature of brain damage is different for every individual patient, it seems logical to expect that deteriorations of performance due to different deficiencies can be predicted with different tests. Given the diversity of brain injuries, both qualitatively and quantitatively, the notion of using one predictive battery of tests for all brain damaged persons may be considered a rather optimistic idea. Moreover, for the worst cases of brain injury one does not need a test to determine that the patient cannot drive anymore, so that the range in test and driving performance of patients that are tested is restricted.

5 CONCLUSION

The results of this study showed that some of the selected laboratory tests predicted driving performance of stably recovered brain-damaged drivers. However, the amount of variance in on-road driving performance that could be accounted for by these tests was insufficient for the laboratory tests to completely replace on-road driving as the assessment method of the driving fitness of this group of persons.

It seems necessary to thoroughly investigate the validity and reliability of the criterion variable, the on-road driving test. To do so it is necessary to clearly establish what aspects of driving are crucial for driving safety, and consequently for fitness to drive, and what is the most sensitive, valid and reliable method to assess these aspects of driving.

In addition, subsequent research should be directed at assessing the driving fitness of persons with brain damage in (low-cost) driving simulators. Simulator driving might be a more powerful driving fitness assessment method than neuropsychological testing, since the diversity in underlying causes of being unfit to drive after brain-injury might make it difficult to identify unsafe drivers when using only neuropsychological tests.

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[6] From February 1, 1994, the name of the institute has been changed from 'Instituut voor Zintuigfysiologie TNO' (IZF) into 'TNO Technische Menskunde' (TNO-TM), in English: 'TNO Human Factors Research Institute'.

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APPENDIX Results (mean and standard deviation) on driving test and laboratory tasks

(n=38)	mean	s.d.
overall driving performance (rated)	6.279	1.258
flexibility	6.180	1.310
observation	6.000	1.260
traffic rules	6.000	1.200
technical driving	6.414	1.181
temporal aspects	6.000	1.310
PS	*20.105*	*6.261*
SDS	40.737	11.447
TR-tracking	14.803	4.069
TR-rt	665.939 ms	326.707 ms
TR-ratio	0.06	0.24
TR-error%	16.684 %	5.996 %
TE-rt	717.784 ms	418.906 ms
TE-error%	13.605 %	6.261

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

The present study validates four simple neuropsychological tests as tools to assess the driving fitness of brain-damaged patients, i.e., a Perceptual Speed test, the WAIS Symbol-Digit Substitution subtest, a Tracking-Reaction dual task and a Time Estimation task. These tasks focus on perceptual and attentional deficiencies that most brain-damaged patients show. Subjects performed both the laboratory tests and an on-road driving test. The results indicated that, for brain-damaged subjects, performance on both the Perceptual Speed task and the Time Estimation task were significantly correlated with driving performance. Neither of the tests, however, predicted on-road driving to a degree that would justify replacing the on-road driving test that is currently used to assess the driving fitness of brain-damaged patients. When combined with coma duration and driving experience, the Perceptual Speed and Tracking-Reaction tests together could explain 35.3% of the variance in on-road driving performance. More detailed analyses showed that also a combination of these test scores did not provide enough justification to replace on-road driving fitness assessment. All in all, assessing driving fitness of brain-injured persons with the to-be-validated laboratory tests was not justified by the present results. As a consequence alternative tests (e.g., using low-cost driving simulators) need to be developed.

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