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The sensitivity of laboratory tests assessing driving related skills to dose-related impairment of alcohol: A literature review

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ABSTRACT

Laboratory tests assessing driving related skills can be useful as initial screening tools to assess potential drug induced impairment as part of a standardized behavioural assessment. Unfortunately, consensus about which laboratory tests should be included to reliably assess drug induced impairment has not yet been reached. The aim of the present review was to evaluate the sensitivity of laboratory tests to the dose dependent effects of alcohol, as a benchmark, on performance parameters. In total, 179 experimental studies were included. Results show that a cued go/no-go task and a divided attention test with primary tracking and secondary visual search were consistently sensitive to the impairing effects at medium and high blood alcohol concentrations. Driving performance assessed in a simulator was less sensitive to the effects of alcohol as compared to naturalistic, on-the-road driving. In conclusion, replicating results of several potentially useful tests and their predictive validity of actual driving impairment should deserve further research. In addition, driving simulators should be validated and compared head to head to naturalistic driving in order to increase construct validity.

1. Introduction

Many individuals are prescribed psychoactive drugs to relieve symptoms related to mental, sleep or other disorders. A major problem associated with the use of these drugs may be daytime sleepiness and associated impairment of psychomotor functioning during the day, which could adversely affect daily activities, such as automobile driving. The effects of psychoactive drugs on driving have been widely established by either epidemiological or experimental study designs (for reviews see Dassanayake et al., 2011; Elvik, 2013; Mailis-Gagnon et al., 2012; Vermeeren, 2004; Verster et al., 2004). It has been recognized that a standardized behavioural assessment should be part of a structured, standardized protocol for assessing drug induced driving impairment (ICADTS, 1999; Kay and Logan, 2011; Ogden and Moskowitz, 2004; Vermeeren et al., 1994; Walsh et al., 2008).

Driving is a highly complex activity involving a wide range of cognitive, perceptual, and motor activities. The assessment of drug effects on a wide range of relevant driving skills has been advised to progress from laboratory and driving simulator tests, during initial screening, to on-the-road driving tests as the final assessment (ICADTS, 1999). Laboratory tests are generally a first step to screen for a drug's impairing potential in early phase clinical trials, as these tests are cost-effective, easy to administer, and widely available. Tests for initial screening should meet five criteria to be included in clinical trials assessing the effects of drugs on driving. Tests should (a) be standardized, (b) be sensitive to the potential impairing effects of drugs, (c) have established reliability (i.e. consistent results within and across studies), (d) have validity supported by theoretical models of driving behaviour (e.g. Michon, 1985) and (e) be calibrated by benchmark drugs and doses to ensure comparability of results from various research settings. Driving stimulators and on-the-road driving tests should be included in a later stage in clinical trials specifically intended to assess the drug's impairing effects on driving, as these tests have higher external validity (ICADTS, 1999; Kay and Logan, 2011; Vermeeren et al., 1994; Walsh et al., 2008). The problem for initial screening is, however, that it has not been clearly indicated which laboratory tests are most sensitive to detect drug induced impairment and consensus about which laboratory tests should be included to reliably assess drug induced impairment has not yet been reached.

A benchmark drug can be used for assessing the sensitivity of laboratory tests to drug induced impairment. A benchmark drug is a drug with known impairing effects on driving performance. Alcohol is by far the best documented substance which induces

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driving impairment. Alcohol has a clear exponential dose-dependent relationship with accident risk (Borkenstein, 1964; Krüger, 1990; Blomberg et al., 2009) and legally well-accepted criteria for driving under the influence have been established (Brookhuis et al., 2003). Alcohol is considered to be a central nervous system (CNS) depressant and has rather nonspecific effects. At low or moderate doses, alcohol acts primarily as an agonist at the $GABA_A$ receptor, but has also a direct or indirect effect on other neurotransmitter systems, such as glutamate, dopamine, opioids, and serotonin (Chastain, 2006; Vengeliene et al., 2008). This can explain the wide spectrum of impairing effects on performance, which makes it a suitable benchmark drug to assess sensitivity of tests to detect impairment.

A number of reviews have previously been published on the effects of alcohol on cognition and performance (Ferrara et al., 1994; Holloway, 1995; Krüger, 1993; Levine et al., 1975; Moskowitz and Robinson, 1988; Moskowitz and Fiorentino, 2000). The main aim of these reviews was to establish the effects of alcohol on cognitive domains per se. Nevertheless, these reviews provided some type of tests could be suitable to assess driving impairment. They indicated that sensitivity to alcohol impairment was greater in driving tests (e.g. on-the-road and simulated driving) and tests assessing controlled performance (e.g. divided attention and eye–hand coordination) compared to tests assessing automatic performance (e.g. easy tracking and simple and choice reaction time) (Krüger, 1993; Holloway, 1995). In addition, Ferrara and colleagues (1994) indicated that type of tests assessing complex psychomotor performance is required to establish alcohol induced impairment. The most recent review (Moskowitz and Fiorentino, 2000) showed that on-the-road, simulator tests, divided attention paradigms, and measures of drowsiness were most sensitive to low doses of alcohol. Vigilance, tracking, perception, visual functioning and cognitive tests were only sensitive to higher doses of alcohol. However, limited information was provided regarding specific useful tests within the domains related to driving, although it was advised not to use the critical flicker fusion and a simple reaction time test (Moskowitz and Fiorentino, 2000).

Another review recommended the use of several types of tests to assess impairment (Koelega, 1995). In that review it was argued that both vigilance (i.e. automatic behaviour) and divided attention paradigms (i.e. controlled behaviour) should be part of a test battery in assessing impairment. The use of the digit symbol substitution test, critical flicker fusion, digit span, simple and choice reaction time tests was questioned based on a lack of validity and sensitivity of these tests to the effects of alcohol. Again, limited information was provided regarding specific useful tests within driving related domains.

Selection of laboratory tests should be guided by the extent to which the scientific literature supports their ability to detect effects of a benchmark drug, such as alcohol. The aim of the present review was to evaluate the sensitivity of laboratory tests to the dose dependent effects of alcohol, as a benchmark, on performance parameters within five domains of driving related skills. More specifically, we aimed to determine which tests within driving related domains show robust sensitivity to the impairing effects of a low, moderate and high blood alcohol concentration (BAC) on performance over multiple studies.

2. Methods

The literature search was limited to the effects of alcohol on objective measures of skills related to driving performance in experimental studies between 1999 and 2014. This review updates the results of the last review of alcohol on cognitive domains (Moskowitz and Fiorentino, 2000). However, the primary focus is not to assess the effects of alcohol on cognitive domains per se, but to assess the sensitivity of specific laboratory tests to assess impairment induced by alcohol. Using various search engines (i.e. PsychInfo, Medline, and Pubmed) a broad computer search reporting the effect of alcohol on driving related skills was conducted. Search terms were 'alcohol or ethanol' and 'actual driving', 'simulated driving', 'alertness', 'arousal', 'attention', 'processing speed', 'reaction time', 'psychomotor performance', 'vision', and 'executive functions'. Furthermore, cross referencing was performed. The following criteria were used to evaluate the articles, based on the review of Moskowitz and Fiorentino (2000): (1) the laboratory test assessed a cognitive process related to driving (2) more than six participants were included (3) BACs were reported (4) at least one alcohol only treatment was included and (5) a control group design (i.e. cross-over design with a baseline condition or a between subject design with a control group) was used. After considering these criteria, 179 experimental studies were included.

First, the effects of alcohol in laboratory tests assessing cognitive processes related to driving are reviewed for each of the five domains of ability (i.e. the Essential Driving Ability Domains) recently indicated as essential for driving by an expert consensus group (Kay and Logan, 2011): (1) alertness/arousal, (2) attention and processing speed, (3) reaction time/psychomotor functions, (4) sensory-perceptual functioning, and (5) executive functions (Table 1). Tests are classified in the most appropriate domain according to the authors. The domains are chosen to cluster several laboratory tests together in one domain for structure purposes. In general, tests measure more than a single domain and domains can be incorporated in other domains. For example, tests of executive functioning usually include measures which also depend on speed of responding, which may in turn depend on sensory-perceptual functioning. Therefore, tests will be discussed in a broader perspective in which they assess several driving related domains.

Next, the studies assessing alcohol effects on simulated driving were summarized, as these tests are considered to have the second highest external validity and measure various driving skills in a controlled manner. Lastly, measures of actual driving were summarized, as on-the-road tests are generally considered to have the highest external validity in assessing the risk of drugs on driving performance (O'Hanlon, 1984; Verster and Roth, 2011). The sensitivity of the on-the-road driving test to alcohol was used as a reference. This provides the opportunity to compare the sensitivity of initial screening tools with the on-the-road driving test.

The alcohol effects on the dependent variables included in a study were recorded as a significant or non-significant difference from a control group or control condition at any point in time after the administration of alcohol. Several studies reached multiple BACs to assess the sensitivity of multiple dependent variables within a test. The effects of alcohol were divided into three classes (1) a low BAC ranging from 0.01 to 0.30 mg/ml, (2) a medium BAC ranging from 0.31 to 0.60 mg/ml and (3) a high BAC ranging from 0.61 to 1.0 mg/ml. These classes were based on current legal limits for driving under the influence of alcohol, i.e. 0.2, 0.5, and 0.8 mg/ml. A BAC of 0.2 mg/ml is the legal limit in several countries (e.g. Sweden) and in several countries for inexperienced drivers, i.e. drivers having a driving license for less than five years (e.g. in the Netherlands); 0.5 mg/ml is the legal limit for driving in most countries; 0.8 mg/ml is the legal limit in several countries (e.g. the United States and the United Kingdom). Finally, a ratio of significant versus non-significant findings was calculated for each variable as an index of sensitivity. The number of studies included in this ratio provides an indication of the robustness or reliability of the alcohol effects with repeated testing across separate studies. For example, standard deviation of lateral position in the on-the-road highway driving test was measured in 6 studies and significant impairment was found in all studies, indicating 100% impairment (i.e. highly

Table 1
Cognitive domains and associated paradigms.

Cognitive domain	Description	Paradigms
Alertness/arousal	An individual's level of consciousness and being reactive to incoming stimuli.	PVT*, CPT*, CMT, VT, VVT, AVT, DVT, MSLT
Attention and processing speed	Processes involved in becoming receptive to internal or external stimuli (e.g. tests of divided, focused, sustained, or shifting attention)	DAT, PRP, RIP*, FT, OMEDA, UFOV test*, SART*, ANT*
Reaction time/psychomotor functions	Speed of discrete response and coordination of skilled movement	SRT, TCRT, FCRT, CoRT, VPT*, IT, DSST*, PBT, PRT, PT, CTT, CLT, DSMT, SCT, TMT, CST, AOT
Sensory-perceptual functioning	Visual, auditory, proprioceptive, and sensorimotor abilities	SacT, AST, CFF*, DOR, STD, CFF*, MFVPT, OST
Executive functioning	Capacities which are involved in planning, approaching, organizing, monitoring, prioritizing and carrying out various cognitive activities	CGNGT*, GNGT/SST*, Stroop Task, MST*, VSWMT*, Maze Test, Discounting Task, ALT, SST, SET, TSP, GET, RTT, MTS, SOPT, VSWMT*, SeST, NP, ToL, TSP, RET

An asterisk indicates that the test could also be categorized in another domain. Abbreviations: PVT: Psychomotor Vigilance Test; CPT: Continuous Performance Test; CMT: Continuous Monitoring Test; VT: Vigilance Test; VVT: Visual Vigilance Test; AVT: Auditory Vigilance Test; DVT: Digit Vigilance Test; MSLT: Multiple Sleep Latency Test; DAT: Divided Attention Test; PRP: Psychological Refractory Period; RIP: Rapid Information Processing; FT: Flanker Tests, OMEDA: Object Movement under Divided Attention; UFOV: Useful Field of View; SART: Sustained Attention to Response Test; ANT: Attention Network Test; SRT: Simple Reaction Time: TCRT: Two Choice Reaction Time; FCRT: Four Choice Reaction Time; CoRT: Complex Reaction Time; VPT: Visual Probe Task; IT: Inspection Time; DSST: Digit Symbol Substitution Test; PBT: Postural Balance Test; PRT: Pursuit Rotor Test; PT: Pegboard Test; CTT: Critical Tracking Test; CLT: Circular Lights Test; DSMT: Digit Symbol Matching Test; TMT: Trail Making Test; CST: Concept Shifting Test; AOT: Avoidance Obstacle Test; SacT: Saccadic Test, AST: Anti Saccade Test; CFF: Critical Flicker Fusion; DOR: Delayed Ocular Response; STD: Stimulus Tone Discrimination; MFVPT: Motor Free Visual Perception Test; OST: Omitted Stimulus Test; CGNGT: Cued Go/No-Go Test; GNGT: Go/No-Go Test; SST: Stop Signal Test; MST: Memory Scanning Test; VSWMT: Visuo Spatial Working Memory Test; ALT: Associate Learning Test; SeST: Serial Seven Test; NP: Number Pairs; ToL: Tower of London; TSP: Travel Salesperson Problem; RET: Risk Estimation Test.

sensitive) in six out of six studies (i.e. often replicated). It should be noted that this sensitivity index is not a measure of the effect size of alcohol, nor does it control for differences in sample size between studies and publication bias (Elvik, 2011). Results of studies which examined the effects of alcohol in a unique test are only reported in the main text to reduce table sizes.

3. Results

3.1. Effects on laboratory tests assessing driving related skills

3.1.1. Laboratory tests assessing alertness/arousal

Table 2 summarizes the results of thirteen studies assessing the effects of alcohol on tests measuring alertness or arousal.

The effects of alcohol on vigilance, which is the ability to maintain alertness over a prolonged time, in the Psychomotor Vigilance Test (PVT, Dinges and Powell, 1985) have been assessed in seven studies. The PVT is based on a simple visual reaction time test. In general, the duration of vigilance tests is longer than simple reaction time tests. Outcome measures of the PVT are lapses, mean reaction time, 10% fastest responses, median reaction time and inverse reaction time (Basner and Dinges, 2011). Lapses, defined as reaction times larger than 500 ms, are often used in sleep research to indicate a vigilance decrement. Lapses are also the most studied variable in studies assessing the effect of alcohol in the PVT. At a low and medium BAC, no impairment was found, while at a high BAC three out of four studies indicated an increase of lapses. The second most studied variable, mean reaction time, was increased at a medium BAC in one out of three studies, while increased at a high BAC in two out of two studies. Inverse reaction time (I/RT), which emphasizes slowing in the optimum and intermediate response and decreases the contribution of long lapses, was sensitive to alcohol induced impairment at a medium and high BAC in one study (Jongen et al., 2014).

The Continuous Performance Test (CPT; Connors, 1995) measures vigilance with reaction time and accuracy as outcome measures. Two studies used a modified version with an immediate and a delayed response task (Dougherty et al., 1999, 2000). Only the immediate response task is reviewed here, as the delayed response task focuses on memory. Correct detections decreased and omission errors increased at a medium BAC in two out of four studies; at a high BAC in one out of two studies. Commission errors, discriminability as a measure of risk taking, and a ratio of commission

Table 2
Alcohol effects on tests assessing arousal or alertness. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Psychomotor Vigilance Test (*n* = 7)			
Lapses	–/01 (0%)	–/04 (0%)	03/04 (75%)
Mean reaction time	–/01 (0%)	01/03 (33%)	02/02 (100%)
10% fastest responses	–/01 (0%)	01/02 (50%)	01/01 (100%)
Median reaction time	01/01 (100%)	–/01 (0%)	02/02 (100%)
Inverse reaction time	–/01 (0%)	01/01 (100%)	01/01 (100%)
Howard et al., 2007; Jongen et al., 2014; Lamond et al., 2004; Leung et al., 2012; Roehrs et al., 2003; Rupp et al., 2007a; Simons et al., 2012			
Continuous Performance Test (*n* = 4)			
Correct detections/omission errors	–	02/04 (50%)	01/02 (50%)
Commission errors	–	–/04 (0%)	01/02 (50%)
Discriminability/risk taking	–	–/03 (0%)	01/02 (50%)
Ratio commission errors/correct detections	–	–/01 (0%)	01/01 (100%)
Hit reaction time	–	01/02 (50%)	–/01 (0%)
Reaction time variability	–	–/01 (0%)	–/01 (0%)
Reaction time standard error	–	–/01 (0%)	–/01 (0%)
Barkley et al., 2006; Dougherty et al., 1999, 2000; Thompson et al., 2010			
Multiple Sleep Latency Test (*n* = 3)			
Latency	–/01 (0%)	02/03 (67%)	01/01 (100%)
Drake et al., 2003; Roehrs et al., 2003; Rupp et al., 2007b			

Table 3
Alcohol effects on tests assessing attention. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Divided Attention Tests (*n* = 13)			
Secondary choice reaction time test			
Mean reaction time	03/05 (60%)	05/08 (63%)	04/05 (80%)
Accuracy	–	–/03 (0%)	02/05 (40%)
Primary tracking test			
Tracking error	–/04 (0%)	05/07 (71%)	05/05 (100%)
Tracking deviation	–/01 (0%)	02/03 (67%)	01/02 (50%)
Control losses	–	–	02/02 (100%)
Tracking moves	–	–/01 (0%)	–/01 (0%)
Tracking overlap	–	–/01 (0%)	–/01 (0%)
Drake et al., 2003; Grant et al., 2000; Jongen et al., 2014; Kleykamp et al., 2010; Lamers et al., 2003; Ramaekers et al., 2011; Roehrs et al., 2001, 2003; Ronen et al., 2010; Simons et al., 2012; Vermeeren et al., 2002b; Verster et al., 2002; Wright and Terry, 2002			
Psychological Refractory Period (*n* = 4)			
Interference score	–	–/01 (0%)	03/03 (100%)
Fillmore and Van Selst, 2002; Marczinski and Fillmore, 2006; Marczinski et al., 2012; Schweizer et al., 2006			
Rapid Information Processing (*n* = 4)			
Mean digit processing rate	–	–/01 (0%)	05/05 (100%)
Cameron et al., 2001; Fillmore et al., 2009; Fogarty and Vogel-Sprott, 2002; Tiplady et al., 2001			
Flanker Tests (*n* = 4)			
Reaction time	–	–/03 (0%)	01/02 (50%)
Accuracy	–	–/03 (0%)	–/02 (0%)
Bartholow et al., 2003; McKinney et al., 2012; Spronk et al., 2014; Tiplady et al., 2005			
Object Movement under Divided Attention (*n* = 2)			
Time to contact	–/01 (0%)	–/01 (0%)	–
Divided attention error	–/01 (0%)	–/01 (0%)	–
Kuypers et al., 2006; Lamers et al., 2003			
Useful Field of View test (*n* = 2)			
Performance	–	–/01 (0%)	02/03 (67%)
Dry et al., 2012; Simons et al., 2012			
Sustained Attention to Response Task (*n* = 2)			
Commission errors	–	03/03 (100%)	02/02 (100%)
Omission errors	–	–/01 (0%)	–/02 (0%)
Dry et al., 2012; Easdon et al., 2005			

errors and correct detections were not impaired at medium BACs in several studies, while impaired at a high BAC in one out of two studies.

The Multiple Sleep Latency Test (MSLT, Carskadon et al., 1986) is a commonly used measure of physiological sleepiness. Sleepiness is determined by averaging the latency to sleep defined by electroencephalography on a series of four to five standardized nap opportunities. At a medium BAC, latency was reduced in two out of three studies; at a high BAC in one study.

The effects of alcohol on vigilance have been assessed in a number of different but conceptually related paradigms, i.e. the Continuous Monitoring Task (CMT; Falleti et al., 2003), a Vigilance Test as part of Harvard Four Test Battery (Holdstock and de Wit, 2001), the Visual Vigilance Task (VVT, Knowles and Duka, 2004), the Auditory Vigilance Test (AVT; Roehrs et al., 2001), the Digit Vigilance Task (Wesnes et al., 2000) and a Continuous Attention Test (Cameron et al., 2001). Impairment was only found at a medium BAC in the Digit Vigilance Test and the Auditory Vigilance and at a high BAC in the Continuous Attention Test. No impairment was found in the other tests described in this paragraph.

In summary, lapses and mean reaction in the PVT were not reliably sensitive at a medium BAC, while repeatedly impaired at a high BAC. Inverse reaction time in the PVT seems to be a promising variable to assess induced impairment, but has only been assessed in one study. The CPT was not reliably sensitive at a medium and high BAC and seems not preferable to assess impairment. Alcohol induced impairment was found in the MSLT, but the validity of this test for assessing driving impairment is less clear.

3.1.2. Tests of attention and processing speed

Table 3 summarizes the results of 28 studies assessing the effects of alcohol on laboratory tests assessing attention. Attention is not a single concept and several (sub)-tests are needed to measure attention (Posner and Petersen, 1990). A number of facets of attention have been indicated and appear to play an essential role in driving: divided attention, focused or selective attention, sustained attention, and shifting attention.

3.1.2.1. Divided attention tests. Divided attention can be assessed when performing two tasks simultaneously, such as a primary tracking task and a secondary visual search task (Moskowitz, 1973). Primary tracking was not impaired at a low BAC in four studies, while impaired at a medium BAC in five out of seven studies. At a high BAC, tracking error was increased in all five reviewed studies. Reaction time in the secondary task was impaired at a low BAC in three out of five studies and at a medium BAC in five out of eight studies. At a high BAC, increase of reaction time was found in four out of five the studies.

In four studies, divided attention was measured with a Psychological Refractory Period test (PRP; Fillmore and Van Selst, 2002) in which dual task performance is assessed with a go/no-go task and an auditory discrimination task. At a medium BAC, no effect was found on the interference score, which is quantified by calculating the difference between reaction time in the task two when interference is maximal and reaction time in task two when interference is minimal. At a high BAC, impairment was repeatedly observed on the interference score in three studies. In addition, reaction time in the secondary task was impaired at a high BAC, while errors did not increase in the primary and secondary task in one study.

Several other divided attention paradigms have been used to investigate the effects of alcohol. The effects of alcohol were assessed on divided attention in The Object Movement under Divided Attention test (OMEDA, Read et al., 2000) in two studies. No impairment of time to contact and divided attention error was found at a low and medium BAC. At a high BAC, impairment was found in a divided attention test (Tedstone and Coyle, 2004), consisting of a number task (i.e. responding when two even digits appear) and a secondary visual search task. In another study, impairment was found at a medium BAC in a divided attention test consisting of a visuo-spatial and auditory task (Schulte et al., 2001). In one study, divided attention was measured with a primary auditory discrimination task and a secondary letter verification task (Schweizer et al., 2005). At a high BAC, an increase of reaction time in secondary task performance was found, while accuracy was unaffected.

To summarize, divided attention tests with primary tracking performance and secondary visual search have repeatedly been found sensitive to the impairing effects of alcohol. Reaction time in the secondary visual search task was already increased at a low BAC in several studies, and consistently increased at a medium and high BAC in most reviewed studies.

3.1.2.2. Tests assessing other attentional processes. The effect of alcohol in the Rapid Information Processing test (RIP, Fogarty and Vogel-Sprott, 2002) was assessed in four studies. Mean digit processing rate was not impaired at a medium BAC in one study. Impairment of mean digit processing rate was found at a high BAC in five out of five occasions assessed in four studies.

Four studies examined the effects of alcohol in the Eriksen flanker test (Eriksen and Eriksen, 1974), or a modified version, measuring selective attention. Accuracy and reaction time were unaffected at a medium BAC in one study, while impaired at a high BAC in one study (McKinney et al., 2012). At a high BAC, impairment was found in two out of two studies. Another study reported performance impairment at a high BAC, while no impairment was indicated at a medium BAC in a modified version (i.e. the Arrow Flanker Test) (Tiplady et al., 2005). Furthermore, no effects at a medium and high BAC in a modified version of the Eriksen Flanker were found (Bartholow et al., 2003).

The Useful Field of View test (UFOV; Ball et al., 1990) assesses information processing speed, divided attention and selective attention. At a medium BAC, no impairment was found, while impairment was found at two high BACs in one study (Dry et al., 2012); in another study, no impairment was found at a high BAC in the selective attention subtest (Simons et al., 2012).

The Sustained Attention to Response Test (SART, Dry et al., 2012) was used to assess the effects of alcohol on sustained attention and inhibition. Accuracy, measured as commission errors, was decreased at a medium and high BAC in two studies. Omission errors were unaffected by a medium and high BAC in one study.

The Attention Network Test (ANT; Fan et al., 2002) measures three independent attentional networks (i.e. orienting, alerting, and executive network) by using several cue and target conditions. One study assessed the effects of alcohol in the ANT and found that overall reaction time and executive attention were impaired at a high BAC, while no impairment was found at a low and medium BAC (Jongen et al., 2014). The orienting and alerting network were not affected by any BAC.

Several single studies examined the effects of alcohol in different attentional tasks. At a medium BAC, accuracy was decreased in an Inattentional Blindness Test (Clifasefi et al., 2006) and reaction time increased in a Covert Shift to Attention Test assessing shifting attention (Schulte et al., 2001). No effect was found on reaction time or accuracy in a Number Cancellation Test (Clarisse et al., 2004). At a high BAC, reaction time of correct items was increased, while no impairment was found at the number of incorrect responses in a Little Man Test, assessing spatial attention (Farquhar et al., 2002). In a Spatial Attention Task, no effects were found (McKinney et al., 2012).

Tests assessing other attentional processes were not reliably sensitive to the impairing effects of alcohol at a medium BAC. The SART is the only test which can be a potential screening tool to assess induced impairment of sustained attention, as accuracy was impaired at a medium BAC in two studies. However, the number of studies demonstrating the sensitivity of the SART is still limited.

3.1.3. Tests of reaction time and psychomotor functioning

The control of a vehicle depends upon motor coordination and visual-motor abilities. The ability to appropriately apply the brakes of a vehicle is dependent upon psychomotor functions and perceptual speed. Similarly, the individual's ability to avoid a collision is dependent upon the speed with which they can begin implementing the appropriate action.

3.1.3.1. Tests of reaction time. The effects of alcohol on tests assessing reaction time were assessed in sixteen studies, which are summarized in Table 4.

Alcohol effects were assessed on simple reaction time tests in nine studies. A simple reaction time test is a very short test which requires responding by a single button press. In half of the reviewed studies (i.e. four out of eight studies), reaction time was increased at a medium BAC. At a high BAC, an increase of reaction time was found in two out of four studies.

Six studies examined the effects of alcohol in a two-choice reaction time test, in which it is required to choose one out of two response choices. In one study, no effect on reaction time was found at a low BAC. In five out of nine measurements, assessed in eight studies, an increase of reaction time at a medium BAC was found; all five reviewed studies indicated impairment at a high BAC.

The effects of alcohol on a four choice reaction time task were administered in four studies. One study found an increase of reaction time, but no decrease of accuracy at a medium BAC (Martin and Garfield, 2006), while another study did not find an effect at a medium BAC on reaction time and errors (Tiplady et al., 2004). At a high BAC, errors were increased in three out of three studies.

No effects were found at a medium BAC in complex reaction time tests. In one study, the task was to response whether two cards matched in colour (Falleti et al., 2003); the other study did not report the explanation of the complex reaction time test (Roehrs et al., 2001).

Two studies examined the effects of alcohol on a Visual Probe Task (VPT, Miller and Fillmore, 2011), in which the participant had to respond to a visual probe, which was preceded by an image. At a medium and high BAC, no effects were found on mean fixation time and mean probe reaction time in one study; in another study, no effect on mean probe reaction time, while mean fixation reaction time increased at a medium BAC (Roberts et al., 2013).

Dry and colleagues (2012) assessed the effects of alcohol on the test of Inspection Time (IT, Deary and Stough, 1996), which is a motor free two choice reaction time test. Reaction time was increased in a dose related manner, in which impairment was found at a medium and high BAC.

In summary, simple reaction time tests lack consistent sensitivity to the impairing effects of medium and high BACs. The sensitivity to alcohol impairment increases when the complexity of the test is higher, for example when a choice reaction time is administered. The test of Inspection Time seems to be a promising laboratory task to assess impairment, but so far only one study assessed alcohol induced impairment in this test.

Table 4
Alcohol effects on reaction time tests at low, medium, and high BACs.

Simple reaction time task (*n* = 9)	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Reaction time	–/01 (0%)	04/08 (50%)	02/04 (50%)
Accuracy	–/01 (0%)	–/01 (0%)	–/01 (0%)
Falleti et al., 2003; Hernandez et al., 2006; Iudice et al., 2005; Martin and Garfield, 2006; McKinney et al., 2012; Miller and Fillmore, 2011; Roehrs et al., 2001; Tagawa et al., 2000; Wesnes et al., 2000			
Two choice reaction time task (*n* = 8)			
Reaction time	–/01 (0%)	05/09 (56%)	06/06 (100%)
Accuracy	–/01 (0%)	01/06 (17%)	01/04 (25%)
Falleti et al., 2003; Fillmore, 2010; Grant et al., 2000; Kleykamp et al., 2010; Liguori et al., 1999; Roberts et al., 2013; Tagawa et al., 2000; Wesnes et al., 2000			
Four choice reaction time task (*n* = 4)			
Reaction time fixed sequence	–	–/01 (0%)	–/03 (0%)
Accuracy fixed sequence	–	–/01 (0%)	02/02 (100%)
Reaction time random sequence	–	01/01 (100%)	01/02 (50%)
Accuracy random sequence	–	–/01 (0%)	02/02 (100%)
Mackay et al., 2002; Martin and Garfield, 2006; Tiplady et al., 2001, 2004			
Complex reaction time task (*n* = 2)			
Reaction time	–	–/02 (0%)	–
Accuracy	–	–/02 (0%)	–
Falleti et al., 2003; Roehrs et al., 2001			
Visual probe task (*n* = 2)			
Mean fixation time	–	01/02 (50%)	01/02 (50%)
Mean probe reaction time	–	–/02 (0%)	–/02 (0%)
Miller and Fillmore, 2011; Roberts et al., 2013			

3.1.3.2. Tests of psychomotor performance. Table 5 summarizes the results of 48 studies examining the effects of alcohol on laboratory tests assessing psychomotor performance.

The effects of alcohol on the Digit Symbol Substitution Test (DSST, Wechsler, 1958) were assessed in 20 studies. The DSST measures several psychomotor and cognitive functions at the same time such as information processing speed, motor coordination and working memory (Riedel et al., 2006). In the DSST, it is required to match digits with corresponding symbols, and can be administered as a paper and pencil test (Wechsler, 1958) or as a computerized version (McLeod et al., 1982). At a low BAC, the amount of correct responses was not affected in one study. Four of the eleven reviewed studies found effects at a medium BAC on correct responses in the DSST; at a high BAC, impairment was found in sixteen out of seventeen studies.

Postural balance tests have been categorized as a test of psychomotor performance, although it measures psychomotor performance differently (i.e. automatic behaviour versus controlled behaviour) compared to other tests reviewed in this section. The effects of alcohol on postural balance were assessed in twelve studies. During this test, participants have to maintain balance in an upright position with eyes open or eyes closed. Most studies examined the effects of alcohol on balance standing on both feet with eyes closed. No impairment was found at a low BAC in two studies. Impairment was found at a medium BAC in three out of five studies. At a high BAC, all four reviewed studies indicated balance impairment. Furthermore, postural balance was assessed with eyes closed while standing on one leg in five studies. At a medium BAC, postural balance impairment was found in one out of three studies. At a high BAC, postural imbalance was found in three out of three studies. Lastly, one study assessed the effects of alcohol on balance standing upright on both feet with eyes open; postural balance was not impaired at a low BAC, while impaired at a medium and high BAC (Jongen et al., 2014). One study assessed the effects of a high dose of alcohol on balance with a Maddox wing device, but found no impairment at a high BAC (Hernández-López et al., 2002).

Nine of the reviewed studies assessed the effects of alcohol on a Pursuit Rotor Task (PRT; Fillmore et al., 2002), which measures psychomotor performance as the percentage of time on target. Two out of four studies reported a reduction of percentage time on target at a medium BAC. At a high BAC, impairment was found in six out of six studies.

The effects of alcohol in the Critical Tracking Test (CTT, Jex et al., 1966) were assessed in seven studies. Lambda, the critical frequency in which a control loss occurs during a task in which the participant has to control a displayed error signal, was impaired at a low BAC in one out of two studies. At a medium BAC, impairment was found in three out of four studies. One study found no effect on the root mean square of tracking error at a medium BAC (Verster et al., 2002). At a high BAC, impairment of tracking performance was found in two out of three studies.

A Grooved Pegboard Test (GPT, Ostling and Fillmore, 2010), which measures motor coordination by assessing the time to pick up pegs and 25 filling holes, was administered in six studies. At a medium BAC, completion time increased in one out of two studies. In five out of five studies, an increase of completion time was found at a high BAC.

Five studies assessed alcohol effects in the Circular Lights Task (CLT, Griffiths et al., 1984), a reaction time task which involves rapid hand–eye coordinated movement. Reaction time increased at a medium and high BAC in three out of three studies, respectively.

Alcohol effects have been assessed at several other tests assessing psychomotor performance. In the Digit Symbol Matching Test (DSMT, Tiplady et al., 2001), participants have to use a yes/no response whether a digit-symbol pair corresponds to the key table. Impairment was found on reaction time of correct responses and number of errors at a high BAC in three studies. In one study, number of errors was increased, while no effect was found on reaction time of correct responses at a high BAC (Tiplady et al., 2003). At a medium BAC, no impairment was indicated on completion time in the Trail-Making Test (TMT, Reitan, 1958), as a measure of psychomotor performance and cognitive flexibility. In a Concept Shifting Test (CST, Van der Elst et al., 2006), an equivalent of the TMT, no impairment was found on reaction time and inference at a low, medium and high BAC (Jongen et al., 2014). One study assessed the effects at two medium BACs in an Avoidance Obstacle Task (Hegeman et al., 2010) and found impairment at failure rate and response times.

To summarize, psychomotor performance is most often assessed with the DSST, which was repeatedly sensitive only at a higher BAC. However, the DSST generally failed to be sensitive to

Table 5
Alcohol effects on tests assessing psychomotor performance. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Digit Symbol Substitution Test (*n* = 20)			
Correct trials	–/01 (0%)	04/11 (36%)	16/17 (94%)
Attempted trials	–	–/03 (0%)	04/04 (100%)
Reaction time	–	–	02/02 (100%)
Brasser et al., 2004; Brumback et al., 2007; Cameron et al., 2001; Dumont et al., 2008; Evans and Levin, 2003, 2004; Hernandez et al., 2006; Holdstock and de Wit, 1999, 2001; Jongen et al., 2014; King et al., 2002; Kleykamp et al., 2010; Mackay et al., 2002; McCaul et al., 2000; Roehrs et al., 2001; Schweizer et al., 2006; Tiplady et al., 2001; Thompson et al., 2010; Vanakoski et al., 2000; Verster et al., 2002			
Postural Balance Tests (*n* = 12)			
Balance both feet eyes closed	–	03/05 (60%)	04/04 (100%)
Balance on one leg with eyes closed	–/02 (0%)	01/03 (33%)	03/03 (100%)
Balance both feet eyes open	–/01 (0%)	01/01 (100%)	01/01 (100%)
Brasser et al., 2004; Dumont et al., 2010; Evans and Levin, 2003, 2004; Hernandez et al., 2006; Jongen et al., 2014; Kleykamp et al., 2010; Liguori and Robinson, 2001; Liguori et al., 1999, 2002; McCaul et al., 2000; Wesnes et al., 2000			
Pursuit Rotor Task (*n* = 9)			
Percentage time on target	–	02/04 (50%)	06/06 (100%)
Smooth pursuit gain	–	01/02 (50%)	02/02 (100%)
Dumont et al., 2010; Fillmore et al., 2002; Fillmore, 2003; Fogarty and Vogel-Sprott, 2002; Harrison and Fillmore, 2005b; Holdstock and de Wit, 1999; King et al., 2002; Roche and King, 2010; Tagawa et al., 2000			
Critical Tracking Test (*n* = 7)			
Lambda	01/02 (50%)	03/04 (75%)	02/03 (67%)
Jongen et al., 2014; Kuypers et al., 2006; Lamers et al., 2003; Ramaekers et al., 2011; Simons et al., 2012; Vermeeren et al., 2002a,b; Verster et al., 2002			
Pegboard Test (*n* = 6)			
Overall time of all pegs	–	01/02 (50%)	05/05 (100%)
Number of pegs dropped	–	–/01 (0%)	01/01 (100%)
Brumback et al., 2007; Fillmore and Weafer, 2012; Marczinski et al., 2012; Miller et al., 2012; Ostling and Fillmore, 2010; Roberts et al., 2013			
Circular Lights (*n* = 5)			
Reaction time	–	03/03 (100%)	03/03 (100%)
Number of responses	–	01/01 (100%)	02/02 (100%)
Number correct	–	–/01 (0%)	01/01 (100%)
Brasser et al., 2004; Kleykamp et al., 2010; McCaul et al., 2000; Mintzer and Griffiths, 2001, 2002			
Digit-Symbol Matching (*n* = 5)			
Number of incorrect	–	–	05/05 (100%)
Reaction time of correct responses	–	–	04/05 (80%)
Cameron et al., 2001; Farquhar et al., 2002; Tiplady et al., 2001, 2003, 2004			
Trail Making Test (*n* = 2)			
Reaction time part a	–/01 (0%)	–/02 (0%)	01/02 (50%)
Reaction time part b	–/01 (0%)	–/02 (0%)	01/02 (50%)
Dry et al., 2012; Sklar et al., 2014			

the impairing effects at a medium BAC. In contrast, The CTT, CLT, and postural balance tests were found to be sensitive at a medium and high BAC in most studies and seem therefore preferable to assess psychomotor impairment.

3.1.4. Sensory-perceptual function

Sensory-perceptual functions (i.e. visual, auditory, proprioceptive, and sensorimotor abilities) are necessary functions to performance the driving task. Table 6 summarizes the results of 23 studies assessing the effects of alcohol on these functions.

In eleven studies, the effects of alcohol were assessed in a Saccadic Task (Abroms et al., 2006), in which is required to make a single saccade to the location of the target. The reaction time or latency was impaired at a medium BAC in four out of seven studies. One study found no impairment at a low BAC (Nyberg et al., 2004). At a high BAC, five out of six studies found impairment.

In an Anti Saccade Task (AST; Blekher et al., 2002), participants have to redirect their gaze away from the target. The effects of alcohol in the AST were assessed in six studies. Reaction time was increased at a medium BAC in one out of three studies. At a high BAC, an increase of reaction time was found in four out of four studies.

Alcohol effects in a test of Simple Tone Discrimination (Fillmore and Van Selst, 2002) were assessed in four studies, but no impairment was found at a medium or high BAC. Four studies assessed the effects of alcohol on Critical Flicker Fusion (CFF, Liguori and Robinson, 2001). In this task, participants have to indicate the frequency at which flickering light became fused light or vice versa. No impairment was found at a medium or high BAC in all four studies.

Two studies assessed the effect of alcohol on a Delayed Ocular to Response Task (DORT, Abroms et al., 2006), which measures the ability to intentionally inhibit the tendency to make a reflexive saccade. In both studies, impairment of premature saccades was found at a medium and high BAC.

One study administered the Motor Free Visual Perception Test (MFVPT, Calhoun et al., 2005), but found no effect on reaction time and accuracy at a medium and high BAC. The Omitted Stimulus Task (OST, Hernandez et al., 2006) was used in one study. At a medium and high BAC, visual premotor reaction time (i.e. the amount of time required to perceive and interpret a stimulus and decide on a response before any movement) was impaired, while all other variables were unaffected at a medium BAC.

In summary, the DORT was sensitive to the impairing effects of alcohol doses reaching medium BACs, but only in two studies. In addition, more than half of the studies indicated alcohol induced impairment in a saccadic test. Therefore, these tests seem preferable to assess impairment in contrast to the test of critical flicker fusion and simple tone discrimination, which were repeatedly insensitive to any BAC. However, the validity of all these tests is questionable to assess driving impairment, as these tests generally only measure sensory perceptual functions.

Table 6
Alcohol effects on tests assessing sensory-perceptual functions. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Saccadic Task (*n* = 11)			
Reaction time/latency	–/01 (0%)	04/07 (57%)	05/06 (83%)
(Peak) saccadic velocity	01/01 (100%)	02/04 (50%)	05/05 (100%)
Accuracy	01/01 (100%)	–/04 (0%)	02/04 (50%)
Percentage accepted	–	–/01 (0%)	–/01 (0%)
Abroms et al., 2006; Blekher et al., 2002; Dumont et al., 2010; Holdstock and de Wit, 1999; King et al., 2002; Marinkovic et al., 2013; Miller and Fillmore, 2011; Nyberg et al., 2004; Roche and King, 2010; Vassallo and Abel, 2002; Vorstius et al., 2008			
Anti Saccade Task (*n* = 6)			
Reaction time/latency	–/01 (0%)	01/03 (33%)	04/04 (100%)
Accuracy	–	–/03 (0%)	–/04 (0%)
Velocity	–	–/01 (0%)	03/03 (100%)
Percentage accepted	–	01/01 (100%)	01/01 (100%)
Blekher et al., 2002; Khan et al., 2003; Marinkovic et al., 2013; Roche and King, 2010; Vassallo and Abel, 2002; Vorstius et al., 2008			
Simple Tone Discrimination (*n* = 4)			
Reaction time	–	–/02 (0%)	–/03 (0%)
Fillmore and Van Selst, 2002; Marczinski and Fillmore, 2006; Marczinski et al., 2012; Marinkovic et al., 2000			
Critical Flicker Fusion (*n* = 4)			
Critical flicker fusion values	–	–/03 (0%)	–/04 (0%)
Iudice et al., 2005; Liguori et al., 1999; Liguori and Robinson, 2001; Liu and Ho, 2010			
Delayed Ocular Response Task (*n* = 2)			
Premature saccades	–	02/02 (100%)	02/02 (100%)
Reaction time of valid saccades	–	01/02 (50%)	02/02 (100%)
Accuracy of valid saccades	–	01/01 (100%)	01/01 (100%)
Late saccades	–	–/01 (0%)	–/01 (0%)
Abroms et al., 2006; Weafer and Fillmore, 2012b			

3.1.5. Tests of executive functioning

Executive functioning is an umbrella term for the management of cognitive processes (Elliott, 2003). Executive functions are considered to play a role in driving as they impact upon the driver's planning, ability to avoid crashes, and to assess risk. Measures of executive functioning typically involve mental flexibility, adaptive problem solving, abstract reasoning, impulse control, risk taking, organizational ability, or planning. Table 7 summarizes the results of 55 studies examining the effects of alcohol on tasks assessing executive functions.

In 22 studies, the effects of alcohol have been assessed in the cued go/no-go task (Fillmore, 2004), in which participants have to respond to a go target or inhibit a response to a no-go target, preceded by either a go or a no-go cue. The main outcome variable is the proportion of commission errors, in which participants fail to inhibit a response after a go cue and a no-go target. At a medium BAC, an increase of commission errors was found in all eight reviewed studies; at a high BAC in all 23 occasions, based on 22 reviewed studies. Other variables, such as reaction time to go targets (preferably categorized as a reaction time test instead of a measure of executive functioning) preceded by a go or a no-go cue and commission errors after no-go cue and a no-go target, were less sensitive to the impairing effects of alcohol. Omission errors (i.e. no response at all after a go target) were infrequent in all studies and not sensitive to medium and high BACs.

The effects of alcohol in the Go–No Go Test or the Stop Signal Test (Fillmore et al., 2002) were examined in eleven studies. The test is slightly different compared to the cued go/no-go task in that participants have to make quick key responses to go signals and to inhibit any response when a stop signal is presented, without differentiating between go and no-go targets. Main study variables are commission errors (i.e. a failure to inhibit a response), reaction time to a go signal, accuracy to go signal, and a stop signal reaction time (SSRT). Commission errors were not increased at a medium BAC in three studies. At a high BAC, an increase was found in seven of nine occasions. Reaction time and accuracy to go signals was not impaired at a medium BAC in four studies. Reaction time to go signals increased at a high BAC in two out of eight occasions, assessed in seven studies. Accuracy to go signals was impaired at a high BAC in one out of seven studies. The SSRT was increased at a medium BAC two out of four times, assessed in three studies. At a high BAC, impairment was found in three out of four studies.

A maze test, either the Gibson Spiral Maze Test (Gibson, 1985) or the Rectangular Maze Test (Cameron et al., 2001), in which it is required to trace a path, was administered in seven studies. At a medium BAC, no increase of errors was found in three studies. In addition, total time to complete the maze was not increased at a medium BAC in two studies. At a high BAC, an increase of errors was found on eight out of nine measurements, based on seven studies. In two of these studies impairment was found at a high BAC in both the Gibson Spiral Maze and the Rectangular Maze Test (Tiplady et al., 2001, 2003).

The effects of alcohol in the Stroop Task (Stroop, 1935) or a modified Colour Naming Test (CNT, Fillmore et al., 2000a,b) have been assessed in six studies. The Stroop Task measures selective attention and response conflict, in which participants have to respond in several conditions, i.e. congruent, in which the word of a colour and the colour of the word are congruent, and an incongruent condition, in which the word of a colour and the colour of the word are incongruent. The most assessed variables are the reaction time of these conditions and an interference score (i.e. comparing the reaction time of both conditions). In two different studies, no impairment of the interference score was found at a medium and high BAC. In two out of three studies, impairment was found at a high BAC in the incongruent colour naming condition. No impairment was found at a high BAC in the congruent word reading condition in three studies. In the modified CNT, mean reaction time in the negatively primed condition (i.e. the distractor in the previous trial became the probe in a subsequent trial) was impaired at a medium and high BAC in two studies. No impairment was found in the unprimed or positively primed condition at a medium and high BAC in one study.

Five studies examined the effects of alcohol on a Memory Scanning Test (MST, Sternberg, 1975), in which it is required to remember a set of three, four, or five digits and to respond whenever a memorized set was presented. No increase of errors

Table 7
Alcohol effects on tests assessing executive functions. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Cued go/no-go task (*n* = 22)			
Commission errors after go cue and no-go target	–	08/08 (100%)	23/23 (100%)
Reaction time to go cue and go target	–	01/08 (13%)	06/18 (33%)
Reaction time to no-go cue and go target	–	04/04 (100%)	11/16 (69%)
Commission errors after no-go cue and no-go target	–	02/05 (40%)	03/11 (27%)
Omission errors	–	–/01 (0%)	–/10 (0%)
Abroms et al., 2003; Abroms and Fillmore, 2004; Fillmore, 2004, 2010; Fillmore et al., 2005, 2008, 2009; Fillmore and Weafer, 2004, 2012; Marczinski and Fillmore, 2005a,c; Marczinski et al., 2005, 2007, 2011; Miller et al., 2012; Ostling and Fillmore, 2010; Ramaekers and Kuypers, 2006; Reynolds et al., 2006; Van Dyke and Fillmore, 2014; Weafer et al., 2009; Weafer and Fillmore, 2012a,b			
Go/No-Go task/Stop Signal Task (*n* = 11)			
Commission errors/failure to inhibit	–	–/03 (0%)	07/09 (78%)
Reaction time to go signal	–	–/04 (0%)	02/08 (25%)
Accuracy to go signal	–	–/04 (0%)	01/07 (14%)
Stop signal reaction time (SSRT)	–	02/04 (50%)	03/04 (75%)
Sensitivity (*d'*)	–	–	01/02 (50%)
Caswell et al., 2013; Corbin and Cronce, 2007; de Wit et al., 2000; Fillmore and Vogel-Sprott, 2000; Fillmore and Blackburn, 2001; Finn et al., 1999; McCarthy et al., 2012; Ortner et al., 2003; Ramaekers and Kuypers, 2006; Ramaekers et al., 2011; Reynolds et al., 2006			
Maze Test (*n* = 7)			
Number of errors	–	–/03 (0%)	08/09 (89%)
Total time	–	–/02 (0%)	03/08 (38%)
Cameron et al., 2001; Farquhar et al., 2002; Starkey and Charlton, 2014; Tiplady et al., 2001, 2003, 2004, 2005			
Stroop Task (*n* = 6)			
Mean reaction time-negatively primed	–	01/01 (100%)	02/02 (100%)
Mean reaction time-colour naming (incongruent)	–	–	02/03 (67%)
Mean reaction time-word reading (congruent)	–	–	–/03 (0%)
Stroop interference score	–	–/01 (0%)	–/01 (0%)
Mean reaction time-positively primed	–	–/01 (0%)	–/01 (0%)
Mean reaction time-unprimed	–	–/01 (0%)	–/01 (0%)
Total errors	–	–	–/02 (0%)
Curtin and Fairchild, 2003; Fillmore et al., 2000a,b; Iudice et al., 2005; Liguori and Robinson, 2001; McKinney et al., 2012			
Memory Scanning Test (*n* = 5)			
Accuracy	–	–/02 (0%)	05/05 (100%)
Reaction time	–	–/01 (0%)	02/04 (50%)
Farquhar et al., 2002; Grattan-Miscio and Vogel-Sprott, 2005b; Kleykamp et al., 2010; Tiplady et al., 2003, 2004			
Visuo-spatial Working Memory Task (*n* = 4)			
Accuracy	–	–/04 (0%)	02/02 (100%)
Reaction time	–	–/01 (0%)	–/01 (0%)
Tiplady et al., 2004, 2005; Weissenborn and Duka, 2003; Wesnes et al., 2000			
Stem Completion Task (*n* = 3)			
Controlled process-correct responses	–	01/01 (100%)	02/02 (100%)
Automatic process-correct responses	–	–/01 (0%)	–/02 (0%)
Grattan and Vogel-Sprott, 2001; Grattan-Miscio and Vogel-Sprott, 2005a; Kirchner and Sayette, 2003			
Discounting Tasks (*n* = 2)			
Indifference point	–	–/01 (0%)	01/02 (50%)
Ortner et al., 2003; Reynolds et al., 2006			
Associate Learning Test (*n* = 2)			
Accuracy	–/01 (0%)	01/02 (50%)	01/01 (100%)
Falleti et al., 2003; Roehrs et al., 2003			
Serial Seven Test (*n* = 2)			
Number of errors	–	01/01 (100%)	01/02 (50%)
Number correct	–	–/01 (0%)	01/02 (50%)
Farquhar et al., 2002; Tiplady et al., 2004			
Number pairs (*n* = 2)			
Errors	–	–/01 (0%)	02/02 (100%)
Reaction time correct items	–	–/01 (0%)	–/02 (0%)
Farquhar et al., 2002; Tiplady et al., 2004			
Tower of London (*n* = 2)			
Mean/total reaction time	–	–/01 (0%)	01/02 (50%)
Ramaekers et al., 2011; Weissenborn and Duka, 2003			

was found at a medium BAC in two studies. At a high BAC, consistent impairment was found in five out of five studies.

The effects of alcohol have been examined on several other tests assessing (one part of) executive functions in various studies. Alcohol induced impairment at a medium BAC was found in several tests, such as correct responses in a stem completion test (Grattan and Vogel-Sprott, 2001), number of errors in a Serial Seven Test (Tiplady et al., 2004), working memory performance in a Self Order Pointing Task (Dry et al., 2012), rate of responding in a Stop Light Task (Roehrs et al., 2004) and error rate and reaction time in a Subtle Cognitive Impairment Test (Friedman et al., 2011). At a high BAC, impairment was found in the Stem Completion Test (Grattan-Miscio and Vogel-Sprott, 2005a; Kirchner and Sayette, 2003), the

Serial Seven Test in one out of two studies and in the Self-Ordered Pointing Task in one study (Dry et al., 2012).

However, no impairment was found at a medium BAC in several tests related to executive functions: accuracy in a visuo-spatial working memory task in four studies (Tiplady et al., 2004, 2005; Weissenborn and Duka, 2003; Wesnes et al., 2000), indifference point in an discounting task (Ortner et al., 2003), reaction time of correct responses and errors in a number pairs test (Farquhar et al., 2002), mean reaction time in the Tower of London task (Ramaekers et al., 2011), performance in a travel salesperson problem test (Dry et al., 2012), and mean number of errors in a risk estimation test (Frick et al., 2000).

No impairment at any BAC was found in several tests assessing related aspects of executive functions: a Random Object Span Task (Pihl et al., 2003), the Iowa Gambling Task (Ramaekers and Kuypers, 2006), a Two Choice Impulsivity Paradigm (McCarthy et al., 2012), a Word Fluency Test (Lamers et al., 2003), an Incidental Learning Task (Falleti et al., 2003), Single Key Impulsivity Paradigm and the Information Sampling Task (Caswell et al., 2013).

In summary, the cued go/no-go task has been administered in most studies and was consistently sensitive to the impairing effects at a medium and high BAC. Various other tests related to executive functions have been assessed, but in general failed to indicate impairment at any BAC.

3.2. Effects of driving tests

3.2.1. Simulator driving

Table 8 summarizes the results of 48 studies which measured the effects of alcohol on simulated driving during a single task, a dual task, a car following test or a gap acceptance test.

3.2.1.1. Single tasks. In 37 studies, Standard Deviation of the Lateral Position (SDLP), as measure of basic vehicle control and vigilance, was measured in a single tracking task after ingestion of alcohol. At a low BAC, impairment was found in three out of nine of the reviewed studies; at a medium BAC, eleven out of eighteen studies; and at a high BAC, 26 out of 27 studies.

Mean speed, often measured to indicate whether participants comply with the instructions of keeping a constant speed, was impaired at a medium BAC in three out of ten of the reviewed studies. At a high BAC, mean speed was increased in seven out of sixteen studies. The standard deviation of speed (SDSP), which is an index to indicate the ability to keep a constant speed, was increased at a medium BAC in two out of eight studies. At a high BAC, four out of six studies indicated impairment of SDSP. Several variables, such as number of accidents and line crossings were found insensitive to the effects of alcohol in most studies.

Steering rate, measured as the degree of steering wheel deviation, was impaired at a medium BAC in two out of four studies. At a high BAC, impairment was found in three out of five times, assessed in four studies. Reaction time to sudden events or detecting other cars, measured as a brake reaction time or a detection time, was sensitive at a medium BAC in four out of five studies. At a high BAC, impairment was found in four out of six studies.

3.2.1.2. Dual tasks. Divided attention can be measured in a driving simulator in a controlled manner by conducting simulator driving as primary task and responding to stimuli as a secondary task. The main variables are the mean reaction time in the secondary task and the standard deviation of lateral position (SDLP) in the primary task. All other variables are reported in Table 8.

In the studies reviewed, no impairment of mean reaction time in the secondary task was found at a low BAC in four studies. At a medium BAC, impairment of mean reaction time was found in six out of eleven studies; at a high BAC, reaction time increased in nine out of fourteen measurements based on ten studies.

Standard deviation of lateral position (SDLP), assessed as primary task parameter in a divided attention paradigm, was assessed in fourteen studies. In one out of four studies, SDLP increased at a low BAC. At a medium BAC, an increase of SDLP was found in four out of ten measurements. An increase of SDLP was found in nine out of eleven BAC measurements, assessed in nine studies.

3.2.1.3. Car-following test. Car following was assessed in nine studies. Mean headway, which is the distance between the lead vehicle and the following car, and coherence, which is the accuracy to speed adaptations by the following car, was assessed in most occasions. At a medium BAC, inter vehicle distance was shorter in one study (Freydier et al., 2014). At low and medium BACs, no impairment was found at any task variables in six studies. At a high BAC, SDLP was the only variable which was impaired in three studies.

3.2.1.4. Gap acceptance test. Four studies examined the effects of alcohol on gap acceptance, which is a measure to assess risk taking and hazard perception (i.e. smaller gap acceptance means larger risk taking behaviour). Accepted gap distance and accepted gap was not impairment at a low, two medium and a high BAC (Veldstra et al., 2012). Accepted gap distance was smaller at a low BAC in one study; a high BAC, impairment was found in one out of two studies.

3.2.2. On-the-road driving tests

Studies assessing the impairing effects of alcohol during actual operation of a car have high external validity, as results can be generalized to actual driving behaviour. Among the more sophisticated tests, the standardized highway driving test is generally regarded as the gold standard to measure drug-induced driving impairment (O'Hanlon, 1984; Verster and Roth, 2011). The primary outcome measure is the standard deviation of lateral position (SDLP), which is an index of 'weaving', assessing basic vehicle control and vigilance. In 1987, SDLP was dose-dependently sensitive to alcohol induced impairment in a closed course test with significant impairment at a BAC of 0.6 mg/ml and greater (Louwerens et al., 1987). The impairing effects of alcohol on SDLP in normal traffic were replicated in later studies: SDLP increased significantly with a medium BAC of 0.4 mg/ml (Ramaekers et al., 2000; Vermeeren et al., 2002a,b), 0.5 mg/ml (Kuypers et al., 2006; Verster et al., 2002) and 0.5 and 0.9 mg/ml in a closed course test (Helland et al., 2013). A secondary measure in the highway driving test is SDSP. The effects of alcohol on SDSP, i.e. the ability to maintain a constant speed, were reported in five studies. No effects were found at a medium BAC in all studies.

In two studies, alcohol effects were also assessed in a car following test (Brookhuis et al., 1994) in which the task was to follow a leading vehicle. In one study no effects were found at a medium BAC (Kuypers et al., 2006), while an effect of standard deviation of headway (i.e. maintaining distance to a leading car) was found at a medium BAC in one study (Ramaekers et al., 2000). City driving in actual traffic was assessed in one study at a medium BAC, but no effects were found on general driving quality and the number of times a participant checked for traffic at intersections (Lamers and Ramaekers, 2001).

In summary, SDLP in the on-the-road highway driving was consistently sensitive to the impairing effects of alcohol at a medium BAC. In contrast, SDLP in simulator studies lacked consistent sensitivity to alcohol at a medium BAC. In addition, car following tests, both on-the-road and in a simulator, were insensitive at a medium BAC. Furthermore, no consistent sensitivity was found at a medium BAC in divided attention paradigms during simulator driving. A gap

Table 8
Alcohol effects on simulator driving performance. Impairment indicated in number of studies reviewed at low, medium and high blood alcohol concentrations.

	≤0.3 mg/ml	0.31–0.6 mg/ml	0.61–1.0 mg/ml
Single tracking test (*n* = 37)			
Standard deviation of lateral position	03/09 (33%)	11/18 (61%)	26/27 (96%)
Mean speed	01/05 (20%)	03/10 (30%)	07/16 (44%)
Standard deviation of speed	–/03 (0%)	02/08 (25%)	08/12 (67%)
Number of accidents	–/02 (0%)	02/08 (25%)	02/09 (22%)
Brake reaction time/detection time	–/01 (0%)	04/05 (80%)	04/06 (67%)
Line crossings (both sides)	–/01 (0%)	01/03 (33%)	04/05 (80%)
Mean lateral position	–/01 (0%)	01/03 (33%)	01/04 (25%)
Steering rate	–/02 (0%)	02/04 (50%)	03/05 (60%)
Number of cone hits	–/01 (0%)	–/02 (0%)	–/01 (0%)
Off-road incidents	–/01 (0%)	01/02 (50%)	02/04 (50%)
Centre line crossings	–	–	03/03 (100%)
Road edge line crossings	–	–/01 (0%)	03/04 (75%)
Failure to stop	–	–	03/03 (100%)
Arnedt et al., 2000, 2001; Banks et al., 2004; Barkley et al., 2006; Barrett et al., 2005; Berthelon and Gineyt, 2014; Burian et al., 2002; Fillmore et al., 2008; Freydier et al., 2014; Harrison and Fillmore, 2005a, 2011; Harrison et al., 2007; Helland et al., 2013; Horne et al., 2003; Howard et al., 2007; Leung and Starmer, 2005; Liguori et al., 1999, 2002; Liguori and Robinson, 2001; Marczinski et al., 2008; Marczinski and Fillmore, 2009; Mets et al., 2011; Quillian et al., 1999; Rupp et al., 2007b; Simons et al., 2012; Sklar et al., 2014; Spaanjaars et al., 2011; Starkey and Charlton, 2014; Thompson et al., 2010; Vakulin et al., 2007; Vanakoski et al., 2000; Van Dyke and Fillmore, 2014; Veldstra et al., 2012; Verster et al., 2009; Weafer et al., 2008; Weafer and Fillmore, 2012a,b; Weiler et al., 2000; Wester et al., 2010			
Dual tasks (*n* = 16)			
Secondary test variables			
Mean reaction time	–/04 (0%)	06/11 (55%)	09/14 (64%)
Accuracy	01/02 (50%)	01/04 (25%)	–/04 (0%)
False alarms	–	–/02 (0%)	01/02 (50%)
Primary simulator test variables			
Standard deviation of lateral position	01/04 (25%)	04/10 (40%)	09/11 (82%)
Mean speed	–	03/04 (75%)	–/04 (0%)
Length of drive	–	01/01 (100%)	01/01 (100%)
Steering error from the ideal curve	–/01 (0%)	01/01 (100%)	02/02 (100%)
Time within target speed	–	–/01 (0%)	02/02 (100%)
Time spend speeding	–	–/01 (0%)	02/02 (100%)
Standard deviation of speed	–	01/02 (50%)	01/02 (50%)
Standard deviation of steering rate	–	02/02 (100%)	–
Line crossings (white/yellow/opposite)	–	–/03 (0%)	–/03 (0%)
Gas/pedal brake pressing	–	–/01 (0%)	–/01 (0%)
Change in steering	–	–/01 (0%)	–/01 (0%)
Allen et al., 2009; Freydier et al., 2014; Hack et al., 2001; Harrison and Fillmore, 2011; Huemer and Vollrath, 2010; Iudice et al., 2005; Lenné et al., 2003, 2010; Leung et al., 2012; Liu and Ho, 2010; Ronen et al., 2008; Rupp et al., 2007b; Starkey and Charlton, 2014; Vanakoski et al., 2000; Verster et al., 2009; Wester et al., 2010			
Car following task (*n* = 9)			
Mean headway	–/03 (0%)	01/03 (33%)	–/04 (0%)
Coherence	–/01 (0%)	–/02 (0%)	–/02 (0%)
Gain	–/01 (0%)	–/02 (0%)	–/02 (0%)
Delay	–/01 (0%)	–/02 (0%)	–/02 (0%)
Standard deviation of headway	–/01 (0%)	–/01 (0%)	–/01 (0%)
Standard deviation of lateral position	–/01 (0%)	–/01 (0%)	03/03 (100%)
Mean lateral position	–	–	–/02 (0%)
Mean speed	–	–	–/02 (0%)
Berthelon and Gineyt, 2014; Freydier et al., 2014; Lenné et al., 2010; Leung and Starmer, 2005; Rakauskas et al., 2008; Simons et al., 2012; Strayer et al., 2006; Veldstra et al., 2012; Weiler et al., 2000			
Gap acceptance task (*n* = 4)			
Accepted distance to approaching car	01/02 (50%)	–/02 (0%)	01/03 (33%)
Accepted gap time	01/02 (50%)	–/02 (0%)	01/02 (50%)
Leung and Starmer, 2005; Simons et al., 2012; Spaanjaars et al., 2011; Veldstra et al., 2012			

acceptance task in a simulator was also not reliably sensitive at a medium and high BAC in multiple reviewed studies.

4. Discussion

The aim of the present review was to evaluate the sensitivity of laboratory tests to alcohol induced impairment, as a benchmark, on performance parameters within five domains of driving related skills. More specifically, we aimed to determine which tests within driving related domains show robust sensitivity to the impairing effects of a low, moderate and high blood alcohol concentration (BAC) on performance over multiple studies. Results at medium and high BACs are summarized in Figs. 1 and 2, respectively. The cued go/no-go task and a divided attention test with primary tracking and secondary visual search were consistently sensitive to the impairing effects of alcohol at a medium and high BAC. These tests seem preferable for future use in a standardized behavioural assessment of potentially drug induced impairment of driving related aspects.

The cued go/no-go task, which assesses inhibitory control, examines the rate of commission errors, i.e. the inability to inhibit a response. It can be argued that this is an important aspect of driving, as inhibitory control is needed for safe driving in order to reduce risk taking behaviour. In the cued go/no-go task, commission errors after a go cue and no-go target was a variable consistently sensitive to the impairing effects at a medium and high BAC in multiple studies. Therefore, it can be a useful screening tool to assess drug induced impairment.

A divided attention test with primary tracking and secondary visual search and a cued go/no-go task were repeatedly sensitive

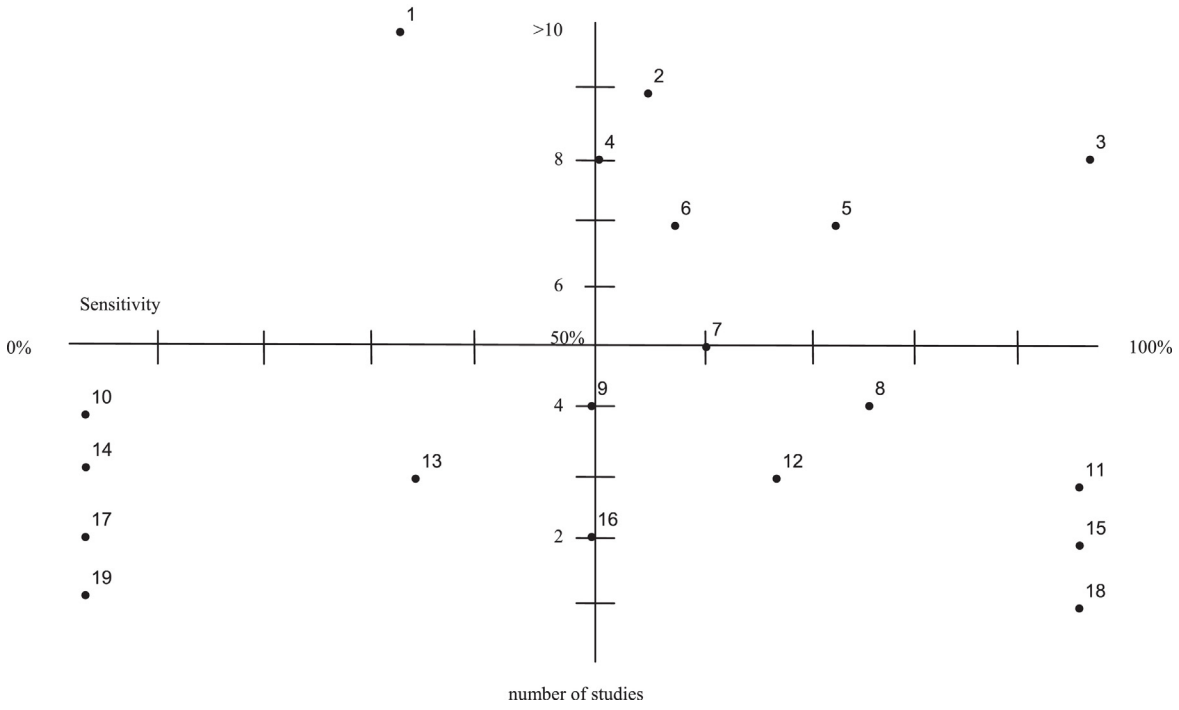

Fig. 1. Sensitivity of laboratory tests to the impairing effects at a BAC of 0.31–0.60 mg/ml in number of reviewed studies. Numbering is based on most studied (1) to least studied (19). 1: Digit Symbol Substitution Test, 2: Two Choice Reaction Time Test, 3: cued go/no-go task, 4: Simple Reaction Time Test 5: Divided Attention Test, 6: Saccidic Test, 7: Postural Balance Test, 8: Critical Tracking Test, 9: Continuous Performance Test. Pursuit Rotor Task, 10: Psychomotor Vigilance Test, Visuo Spatial Working Memory Test, 11: Sustained Attention to Response Test, Circular Lights Test, 12: Multiple Sleep Latency Test, 13: Anti Saccade Test 14: Flanker Test, Critical Flicker Fusion, Go-No-Go Task/Stop Signal Task, Maze Test, 15: Circular Lights Test, Avoidance Obstacle Test, Delayed Ocular Response Test, 16: Visual Probe Task, Pegboard Test, Associate Learning Test, 17: Flanker Test, Complex Reaction Time Test, Trail Making Test, Simple Tone Discrimination, Memory Scanning Test, 18: Stroop Task, Stem Completion Test, Serial Seven Test, 19: Psychological Refractory Period, Rapid Information Processing, Object Movement under Divided Attention, Useful Field of View, Four Choice Reaction Time Test, Discounting Task, Number Pairs, Tower of London.

to the impairing effects of alcohol reaching a medium and high BAC. The most sensitive parameters in the divided attention test were the tracking errors in the primary task and the reaction time in the visual search task. The robust sensitivity of divided attention tests with primary tracking and secondary visual search to the effects of alcohol is in line with previous reviews indicating that divided attention is impaired even at low BACs up to 0.2 mg/ml (Moskowitz and Robinson, 1988; Moskowitz and Fiorentino, 2000). The present review supports the use of a divided attention test with primary tracking and secondary visual search in screening for drug induced impairment. Previous studies showed that this test is also very sensitive to the impairing effects of hypnotics (Leufkens et al., 2009; Leufkens and Vermeeren, 2009; Vermeeren et al., 2002b), anti-histamines (Vermeeren et al., 2002a; Vuurman et al., 2004), antidepressants (Robbe and O'Hanlon, 1995; Wingen et al., 2005) and antipsychotics (Ramaekers et al., 1999).

It can be argued that these two tests cover all driving related domains, i.e. the five Essential Driving Ability Domains (Kay and Logan, 2011) to some extent. Executive functions are needed, i.e. planning and strategy in the divided attention test and inhibitory control in the cued go/no-go task. In both tasks, a motor reaction is obtained to assess reaction time; psychomotor performance and attention is measured in a divided attention and a sustained attention paradigm, respectively. To measure these aspects, both visual functions and a level of arousal are needed.

Other tests, such as the Self-Ordered Pointing Task to assess working memory, test of Inspection Time to assess motor free reaction time and the Sustained Attention to Response Test to measure sustained attention (Dry et al., 2012), were sensitive to the effects of alcohol at medium and high BACs. Therefore they could potentially be useful to assess drug induced impairment. However, the number of studies demonstrating their sensitivity is still limited. Thus, replication is needed to indicate their robustness in indicating impairment.

Tests assessing sensory perceptual functions and arousal have only been studied in a minority of the reviewed studies. This is because of a shift from examination of simple sensory, perceptual, and motor behaviour to more complex measures of cognitive functions, such as divided attention (Ogden and Moskowitz, 2004). Still, several studies assessed the effects of alcohol on tests measuring arousal or vigilance. It has been indicated that tests assessing vigilance differ in the sensitivity to the effects of alcohol (Koelega, 1995). A promising test to assess drug induced impairment is the Psychomotor Vigilance Test (PVT), as it a short and easy to administer test with minimal learning effects. In sleep research, the PVT has been consistently used to indicate impairment induced by sleep deprivation (Doran, 2001; Jewett et al., 1999) and considered for testing fatigue in road transport industry (Dawson et al., 2014). The PVT includes multiple dependent variables which seem differentially sensitive to sleepiness (Basner and Dinges, 2011). In the studies included in the present review, lapses were most examined, but did not seem sensitive to low or moderate doses of alcohol. Results from a recent study suggest that inverse reaction time may be more sensitive to the effects of alcohol (Jongen et al., 2014). This parameter of the PVT could therefore be a potentially sensitive measure to assess drug induced impairment. In addition, performance in the PVT correlated highest with changes in SDLP during on-the-road driving when assessing the effects of sleep deprivation on driving impairment (Jongen et al., 2015). Further studies are therefore needed to confirm the sensitivity of the PVT to drug induced impairment.

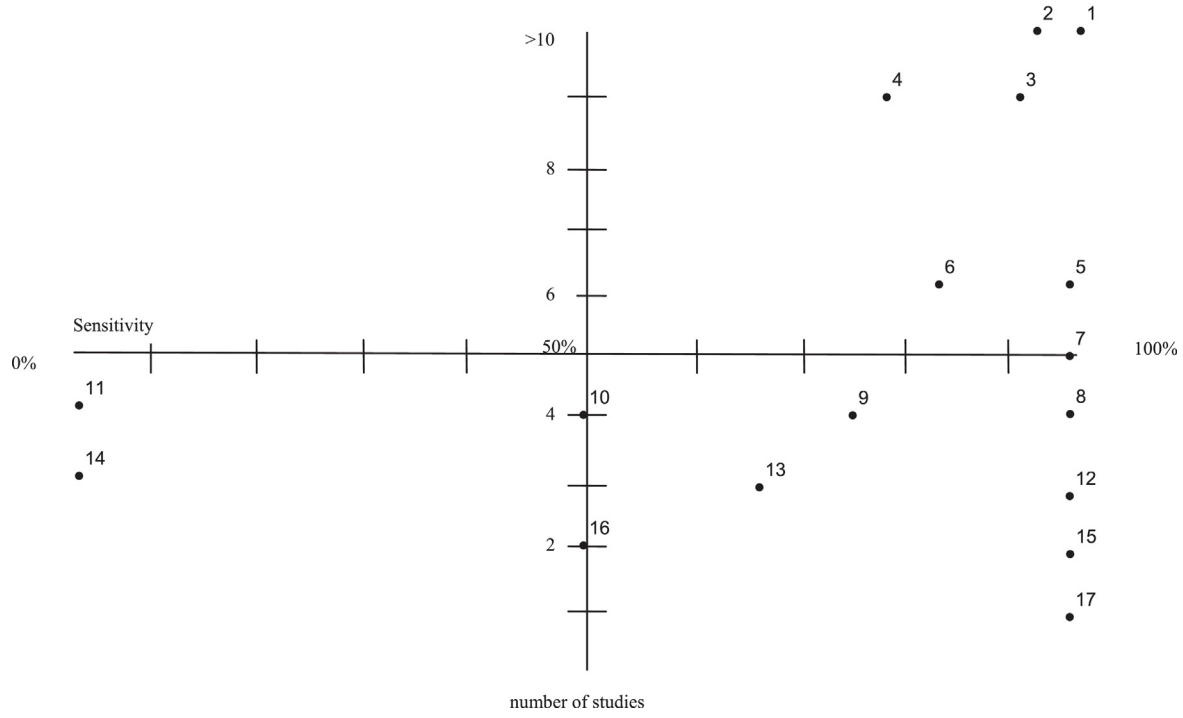

Fig. 2. Sensitivity of laboratory tests to the impairing effects at a BAC of 0.61–1.0 mg/ml in number of reviewed studies. Numbering is based on most studied (1) to least studied (17).* 1: cued go/no-go task, 2: Digit Symbol Substitution Test, 3: Maze Test, 4: Go/No-Go Task/Stop Signal Task, 55: Two Choice Reaction Time Test, Pursuit Rotor Task, 6: Saccadic Test, 7: Divided Attention Test, Rapid Information Processing, Pegboard Test, Digit Symbol Matching Test, Memory Scanning Test, 8: Postural Balance Test, Anti Saccade Test 9: Psychomotor Vigilance Test, 10: Simple Reaction Time Test 11: Critical Flicker Fusion, 12: Psychological Refractory Period, Circular Lights Test 13: Useful Field of View, Critical Tracking Test, 14: Simple Tone Discrimination, 15: Sustained Attention to Response Test, Circular Lights Test, Delayed Ocular Response Test, Stroop Task, Visuo Spatial Working Memory Test, Stem Completion Test, Number Pairs 16: Continuous Performance Test, Flanker Test, Four Choice Reaction Time, Visual Probe Task, Trail Making Test, Discounting Task, Serial Seven Test, Tower of London 17: Multiple Sleep Latency Test, Associate Learning Test. *Numbers do not necessarily correspond to the numbers in Fig. 1.

One of the most frequently used laboratory test overall was the digit symbol substitution test (DSST). Although the effects of alcohol in the DSST have been assessed in a large amount of studies, it generally failed to be sensitive to the impairing effects of alcohol doses reaching a medium BAC. Our results therefore do not support the use of this test in studies aiming to determine drug effects on driving. This is in line with previous concerns regarding the use of this test based on limited validity and sensitivity (Koelega, 1995). This implies that other tests, such as a balance test, Critical Tracking Test or Circular Light Test, should be preferred for assessing potential impairment of psychomotor skills. These tests were repeatedly sensitive to the impairing effects at a medium and high BAC in several studies.

In addition, it was previously indicated that several tests should not be utilized based on the insensitivity to alcohol, such as simple reaction time and critical flicker fusion (Koelega, 1995; Moskowitz and Fiorentino, 2000). The present review supports this notion, as critical flicker fusion was insensitive to any alcohol dose in all studies and inconsistent results were found at a medium and high BAC in simple reaction time tests. In addition, a test of Simple Tone Discrimination was insensitive to the effects of alcohol and should therefore not be used to assess impairment.

The present review also evaluated the effects of alcohol on simulated driving tests. These results were compared with the effects of alcohol on naturalistic on-the-road driving. As expected, SDLP in the highway driving test (O'Hanlon, 1984; Verster and Roth, 2011) was consistently sensitive to a medium BAC. However, SDLP assessed in the simulator was less sensitive, as approximately half of the reviewed studies found no significant increase of SDLP at a medium BAC. A lack of standardization of measuring SDLP could result in these mixed effects (Liguori, 2009). Therefore, SDLP in simulated driving should be validated and compared head to head with SDLP in the highway driving test in order to increase construct validity of SDLP in simulator driving.

Divided attention paradigms in simulated driving were less consistent in indicating alcohol induced impairment in comparison with divided attention in laboratory tasks. Both SDLP as primary task performance and reaction time as secondary task performance were only impaired at a medium BAC in approximately half of the reviewed studies. Again, a lack of standardization of simulator driving could result in these mixed effects (Liguori, 2009). Therefore, a standardization of simulator test procedures is warranted in order to assess drug induced impairment across studies (Kay and Logan, 2011; Walsh et al., 2008). In addition, the advantage of a simulator in comparison with on-the-road driving is to measure drug effects on controlled behaviour, such as risk taking, hazard perception and divided attention in a standardized, controlled manner in a safe setting. To date, however, no robust and sensitive parameters to the impairing effects at a BAC of 0.5 mg/ml have yet been indicated to measure these higher cognitive functions, which extend basic vehicle control as assessed by SDLP. Further research should focus on developing these measures in a simulator setting and indicate the sensitivity of these measures to the effects of alcohol doses reaching a BAC of 0.5 mg/ml.

It should be noted that when performance on a laboratory test is consistently impaired by alcohol, it does not necessarily mean that it is a good measure of impairment induced by drugs other than alcohol. Drugs and alcohol effects can differ in the way how driving behaviour and psychomotor performance are affected (e.g. Kleykamp et al., 2010). In the current review we primarily aimed to assess the sensitivity of laboratory tests for alcohol induced performance impairment, regardless of any qualitative differences between alcohol and other drugs. The clinical relevance of drug induced impairment on these tests can be directly expressed in

alcohol equivalents. In addition, absence of drug effects on these tests is truly an indication of drug safety and cannot be attributed to test insensitivity to drug and alcohol effects.

One limitation of the present review is the lack of providing the validity of laboratory tests to predict actual driving impairment. Previous research indicated that only a tracking test and a divided attention test have modest predictive validity in assessing impairment induced by medicinal drugs (Ramaekers, 2003; Verster and Roth, 2012). Therefore, further research is needed to assess the predictive validity of these tests assessing associations between changes in laboratory test outcomes and changes in SDLP in the on-the-road highway driving test. In addition, test outcomes should be correlated with epidemiological data to indicate whether test outcomes are related to an actual increase of crash risk will under the influence of drugs while driving.

Another limitation is the exclusion of several potentially mediating factors in alcohol induced impairment. Several participant related characteristics may influence the sensitivity to the effect of alcohol, including gender, age, driving experience, expectancy, and tolerance to alcohol. It was recently indicated, however, that participant variables such as age, gender and driving experience are of limited value when assessing the likelihood of impairment (Martin et al., 2013). In addition, several other parameters were not taken into account, such as time-of-day and the sleep-wake cycle.

In conclusion, the most useful tests to include in a behavioural assessment of drug induced driving impairment are a cued go-no/go task and a divided attention test with primary tracking and secondary visual search. These tests were found to be repeatedly sensitive to the impairing effects at a medium and high BAC.

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