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Monitoring drivers' mental workload in driving simulators using physiological measures

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ABSTRACT

Many traffic accidents are caused by, or at least related to, inadequate mental workload, when it is either too low (vigilance) or too high (stress). Creating variations in mental workload and accident-prone driving for research purposes is difficult in the real world. In driving simulators the measurement of driver mental workload is relatively easily conducted by means of physiological measures, although good research skills are required and it is time-consuming. The fact that modern driving simulator environments are laboratory-equivalent nowadays allows full control with respect to environmental conditions, scenarios and stimuli, and enables physiological measurement of parameters of mental workload such as heart rate and brain activity. Several examples are presented to illustrate the potential of modern high-standard driving simulator environments regarding the monitoring of drivers' mental workload during task performance.

1. Introduction

The horrifying number of traffic accidents, implying a firm place in the top three death-rate causation in most industrialised countries, has inspired the development of suitable testing environments to study its major cause, i.e. human behaviour. The research questions that are studied in this field of human behaviour often concern drivers' mental workload, that when inadequate (either too low or too high) may lead to imperfect perception, insufficient attention and inadequate information processing (Lenné et al., 1997; Leung and Starmer, 2005; Ng Boyle et al., 2008; Nilsson et al., 1997; Rakauskas et al., 2008; Thiffault and Bergeron, 2003; Verwey and Zaidel, 1999). The most suitable research environment to study effects on drivers' mental workload is the (advanced) driving simulator, by virtue of its safety, flexibility and laboratory-equivalent potential. Suitable measures to study effects on drivers' mental workload include psychophysiological measures (Kramer, 1991; De Waard and Brookhuis, 1991, 1997; Brookhuis and De Waard, 2009).

Drivers' mental workload, for instance in the sense of fatigue or drowsiness at the low end of workload and stress at the high end, is undoubtedly related to accidents (Brookhuis et al., 2003a). Nevertheless, a workable relationship between drivers' mental workload and accident causation is not easily established in the predominant (traffic) research practice, i.e. in the field. There is little or no control over the conditions the driver was involved in, while measurement of driver state is indirect in all cases, such as in the case of fatigue or even of affected states by psycho-active substances. However, in (driving) simulators control over and measurement of driver's mental workload is relatively easily derived on the one hand. On the other hand, measuring driver's physiology, even in simulators requires good research and technical skills, and it is time-consuming. A modern high-standard driving simulator is sufficiently laboratory-equivalent to allow full control with respect to environmental conditions and stimuli. The infrastructure of the virtual world as well as the scenarios are under full control of the investigator. Additionally, such a research environment enables physiological measurement of parameters such as heart rate and brain activity to measure or monitor mental workload (see also Brookhuis and De Waard, 2009).

Driver mental workload is a consequence of the driving task's demands, among other things. De Waard and Brookhuis (1997) discriminated between underload and overload, the former leading to reduced alertness and lowered attention, the latter to distraction, diverted attention and insufficient capacity and time for adequate information processing. Workload has been studied in relationship with driver impairment (e.g. De Waard, 1996), however, the coupling with accident causation has not been established via a direct link yet (see also Brookhuis et al., 2003b), although simulators provide an unique opportunity to study a surrogate relationship between driver impairment and accident causation in the absence of a direct relationship. Criteria for when impairment is below a certain threshold, leading to accidents, have to be assessed, followed by

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the assessment of concomitant driver mental workload to establish this relationship. Only then accidents and driver mental workload can be realistically related to each other, in conjunction with the origins of unfavourable mental workload conditions such as information overload, boredom and fatigue, or external factors such as consumption of alcohol and drugs. It goes without saying that driving simulators are most practical for this type of research while some people even have the conviction that only driving simulators would be ethically permissible then.

The traffic task environment and traffic itself will only gain in complexity, at least in the near future, with the rapid growth in number of automobiles and electronic applications that are available or under development. The study of the consequences of this forecast, a proliferation of in-vehicle electronic systems will also largely concentrate on simulators because of their flexibility, certainly with respect to measuring (mental) workload. Usually three global categories are distinguished in the field of driver mental workload, i.e. measures of task performance, subjective reports and physiological measures (Brookhuis and De Waard, 2000, 2002). Physiological measures are the most natural type of mental workload index since any task or work, including mental work as well, demands physiological activity by definition. The validity of the measurement of physiological parameters to relate driver mental workload to accident causation, in simulators, is dependent on the degree of reality of the type of simulator used, at least in part.

There are many reasons why the measurement of drivers' mental workload earns great interest these days, and will increasingly enjoy this status in the near future, predominantly because of the changing driving conditions in the last decades. Firstly, the nature of the driving task has changed, at least for professionals, extended from physical strain (e.g. measured by muscle force exertion) to cognitive effort (e.g. measured in brain activity), from quietly interacting with other road users to labouring in highly complex traffic situations, a trend that has not reached a ceiling yet. Secondly, accidents of all sorts are numerous, costly and seemingly ineradicably, and in fact largely attributable to the victims themselves, human beings. Thirdly, human errors in traffic, related to mental workload in the sense of inadequate information processing are among the major causes of the majority of traffic accidents (cf. Smiley and Brookhuis, 1987).

2. Physiological measures

The measurement of physiology in (mental) task situations has been conducted for many years. The methodology is borrowed from the medical field for human factors' and ergonomics' purposes to study operators in workplaces, such as drivers in motor vehicles with respect to their state under various conditions, for instance, while being drowsy, under the influence of psycho-active substances, and while in various mental workload conditions.

More than 35 years ago Kahneman (1973) defined mental workload as directly related to the proportion of the mental capacity an operator spends on task performance. The measurement of mental workload is the specification of that proportion (O'Donnell and Eggemeier, 1986; De Waard and Brookhuis, 1997), in terms of the costs of the cognitive processing, which is also referred to as mental effort (Mulder, 1986). Mental effort is similar to what is commonly meant by doing your best to achieve a certain target level, to even 'trying hard' in case of a strong cognitive processing demand, and is reflected in several physiological measures. The concomitant changes in effort will not show easily in work performance measures because operators are inclined to cope actively with changes in task demands and protect performance (Hockey, 1997). For example, drivers adapt their behaviour in traffic to control safety (Cnossen et al., 1997). Changes in effort are apparent when analysing self-report data of drivers in most cases but concomitant changes in physiological measures including brain activity and heart rate and heart rate variability have also been found (cf. De Waard, 1996).

Mulder (1986) discriminates between two types of mental effort, i.e. the mental effort devoted to the processing of information in controlled mode (computational effort) and the mental effort needed to apply when the operator's energetical state is affected (compensatory effort). Computational effort is exerted to keep task performance at an acceptable level, for instance, when task complexity level varies or secondary tasks are added to the primary task. In case of (ominous) overload extra computational effort could forestall safety hazards in such a way. Compensatory effort takes care of performance decrement in case of, for instance, drowsiness, or fatigue, up to a certain level. Underload due to boredom, affecting the operator's capability to deal with the task demands, might be compensated up to a certain point as well. In case effort is exerted, be it computational or compensatory, both task difficulty and mental workload will be increased. Effort is a voluntary process under control by the operator while mental workload is determined by the interaction between the operator and the task. As an alternative to exerting effort, the operator might decide to change the (sub)goals of the task. Adapting driving behaviour as a strategic solution is a well-known phenomenon that may readily be studied in a driving simulator environment (e.g. Merat et al., 2005). For example, overload because of an additional task such as looking up telephone numbers while driving, is demonstrated in a simulator to be reduced by lowering vehicle speed (see De Waard et al., 2001).

Physical workload but also mental workload has a clear impact on heart rate and heart rate variability (Mulder, 1986, 1988, 1992; De Waard and Brookhuis, 1991), on galvanic skin response (Boucsein, 1992, 2004), blood pressure (Rau, 2001) and respiration (Mulder, 1992; Wientjes, 1992), for instance. Mental workload may increase heart rate and decrease heart rate variability at the same time (Mulder et al., 2004). Other measures of major interest are event-related phenomena in the brain activity during task performance (Kramer, 1991; Kramer and Belopolsky, 2004; Noesselt et al., 2002) and effects of the driving environment on certain task irrelevant facial muscles (Jessurun et al., 1993).

The methodology and some basics of measuring a few relevant physiological parameters as applied in simulators are illustrated in the following paragraphs. They are the cardiovascular parameters heart rate and heart rate variability, the electro cortical parameters of frequency shifts in the electroencephalogram and event-related potentials, and eyelid movements. Heart rate is derived from the electrocardiogram (ECG), which reflects the (electrical) activity of the heart. For the assessment of mental effort not the ECG itself but the variation in time duration between heartbeats provides the interesting information. During task performance operators have to spend (mental) effort, which is usually reflected in increased heart rate and decreased heart rate variability, when compared to resting situations. The general cardiovascular response pattern that is found in many mental effort studies can be characterised by an increase in heart rate and blood pressure and a decrease in heart rate variability (HRV) and blood pressure variability in all frequency bands. This pattern is comparable with a defense reaction and is predominantly found in laboratory studies using short-lasting tasks requiring effortful mental operations in working memory, certain driving tasks for example.

Event-related potentials (ERP), derived as a transient series of voltage oscillations in the brain which can be recorded from the scalp in response to discrete stimuli and responses, provide a detailed picture of mental chronometry. Some ERP components, usually defined in terms of polarity and latency with respect to discrete stimuli or responses, have been found to reflect a number of distinct perceptual, cognitive and motor processes, particularly useful in decomposing the processing requirements of complex tasks such as driving (Strayer and Drews, 2007; Wilschut, 2009). ERPs are being used to study aspects of cognition that are relevant for Human Factors and Ergonomics research such as vigilance, mental workload, fatigue, adaptive aiding, stressor effects on cognition, and automation.

Certain measures of ocular psychophysiology have been identified for their potential to detect minute-to-minute changes in drowsiness and hypo-vigilance, associated with lapses of attention and diminishing alertness during performance. A measure of slow eyelid closure, referred to as percentage of closure (PERCLOS) correlated highly with visual vigilance performance lapses (Wierwille et al., 1994; Wierwille and Ellsworth, 1994), and is now increasingly used to monitor alertness of operators in their working environment, such as (professional) drivers (Mallis and Dinges, 2004).

Three groups of measures will be elaborated in some detail in the remainder of this paper, heart rate (ECG), brain activity (EEG) and alertness monitoring (PERCLOS). The selection criteria for inclusion in this paper were non-intrusiveness and proven effects in relation to (mental) work conditions as studied in simulators. Measurement of most of the included physiological parameters is relatively easy, or at least feasible in the simulator environment, though the measurement of brain activity (event-related potentials in the electroencephalogram) requires considerable training (see Kramer and Belopolsky, 2004; Brookhuis and De Waard, 2009). All of them, however, are relevant within the context of the topic of this paper, i.e. research in simulators.

2.1. Heart rate

The Electrocardiogram (ECG) reflects the (electrical) activity of the heart as can be measured relatively easily through a few (AgAgCl)-electrodes attached to the human chest. Activity of the heart is based on the standard rhythm as instigated by the cardiac sino-arterial node, modulated by innervations from both the sympathetic and parasympathetic (vagal) activity of the autonomous nervous system, dependent on requirements because of physical and/or mental effort. Measuring physical effort is not opportune most of the times in simulators; for the assessment of mental effort the time duration between individual heartbeats and its variability provide the most relevant information. The heart rate (HR) is the number of heart beats within a fixed period of time (usually a minute), while mean heart rate or inter-beat interval (IBI) is the average time duration of the heart beats in that period. Heartbeats have variable time durations with different oscillation patterns, leading to time series with source-characteristic patterns and frequency contents (e.g. Kramer, 1991), called heart rate variability (HRV). During task performance when participants have to spend mental effort, increased HR and decreased HRV are usually clear in comparison to resting situations, effects dependent on amount and type of effort (for an overview see Mulder et al., 2004). In simulator environments HR and HRV are mostly measured and analysed to mental effort as exerted for task requirements. In Fig. 1 an example is given of the effects of different task demands in simulated traffic environments, depending on situational events and challenges, and in this specific experiment also as a function of the use of ±3,4-MethyleneDioxyMethAmphetamine (MDMA), well known as ecstasy (Brookhuis et al., 2004).

There is no doubt that experiments on driving performance with psycho-active substances are difficult to conduct in the real world, i.e. outside simulators. The drivers in this experiment displayed in Fig. 1 clearly show effects of some demanding (sub)tasks. In particular the effect of gap-acceptance tasks on heart rate can be seen as distinctively; judging when to cross a junction and when to accept a gap between oncoming cars in order to turn left increased average heart rate with 5 beats per minute, a large effect, similar to the effect of driving in general as compared with resting conditions. Similar effects of increased task demands were found on HRV (see Brookhuis et al., 2004). The overall increasing effect of MDMA on heart rate itself is stunning, to say the least, up to 15 beats per minute which seems to outshine the effects of mental workload. However, even in the drug condition the effects of mental workload by driving condition are preserved.

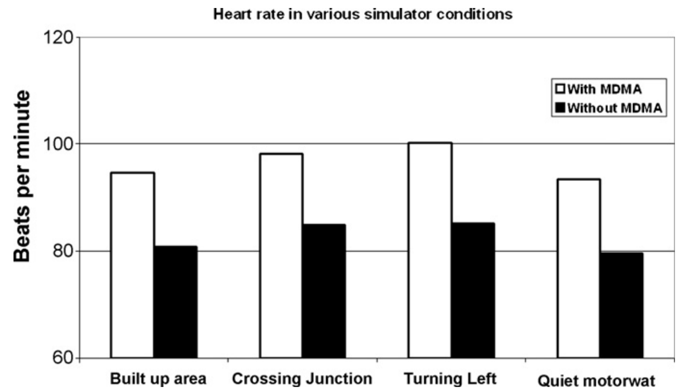

Fig. 1. Average heart rate of 20 participants in an MDMA (ecstasy) experiment during a ride in a driving simulator in four scenarios; driving in a traffic dense built up area, in two gap acceptance situations while crossing junction or turning left, and on a quiet low traffic density highway (from Brookhuis et al., 2004).

2.2. Brain activity

The analysis of the "raw" electroencephalogram, or background EEG, i.e. the collection of low-voltage oscillations between about 1 and 30 Hz, is specifically useful for and indicative of level of activation of the brain. While the event-related potential (ERP) is a transient series of voltage oscillations in the brain, to be discriminated from the background EEG, in response to discrete stimuli and responses. EEG and ERPs are recorded from the scalp through (AgAgCl)-electrodes that, due to the low voltage, have to be amplified considerably, in the order of 1000× which has far reaching consequences for the measurement procedures and circumstances. If EEG is to be measured in driving simulators, the environment preferably has to be electrically shielded in order to avoid amplified noise of, for instance, the common 50 Hz (in Europe). Measuring EEG, even in laboratory circumstances is relatively demanding with respect to skills and facilities.

The content of the background EEG is usually subdivided in bins; from 1 to 5 Hz is called delta-waves, 5–8 Hz theta, 8–12 Hz alpha, and above 12 Hz beta in various subcategories that are not reported here in the light of the restricted use for research in driving simulators. When Beta activity is predominant the participant in the study is generally awake and alert, while the activity dropping to Alpha indicates developing drowsiness, and going further down into the theta region may lead to falling asleep. Delta waves are normally an indication of various phases of actual sleep. The background EEG is by definition considered the most appropriate measure to monitor alertness c.q. vigilance state of operators in specific task situations like drivers while driving long distances (Åkerstedt, 2004), for obvious reasons preferably carried out in simulators.

Specific ERP components, usually defined in terms of polarity (Positive or Negative) and latency (in milliseconds) with respect to a discrete stimulus or response, have been found to reflect a number of distinct perceptual, cognitive and motor processes thereby providing useful information for the decomposition of processing requirements in complex task situations (Fabiani et al., 2000) such as driving motor vehicles in various conditions. ERPs are used to study effects on cognition and performance for more than 40 years now, successfully relating brain activity with operator performance under vigilance conditions, with variable mental workload, while fatigued, with adaptive driving support, and all kinds of stressors, and most importantly, automation (see Wilschut, 2009; Kramer and Belopolsky, 2004; Kramer and Weber, 2000; Byrne and Parasuraman, 1996). For example, Brookhuis et al. (1981) found that increasing task load on a letter search task resulted in increases in the latency but decreases in the amplitude of a late positive component of the ERP, the P300, i.e. a positive peak appearing around 300 ms. Kramer (1991) and Sirevaag et al. (1987) found a different effect in the amplitude of P300s elicited by primary and secondary tasks, which is particularly applicable in driving situations and suitable for application in driving simulators. Driving motor vehicles is pre-eminently a combination of primary and secondary tasks. Strayer and Drews (2007) investigated the effects of cell-phone conversation on attention while driving in a simulator, and demonstrated with the aid of ERPs (decreasing amplitude of the P300) that attention and memory was disrupted while talking over the mobile phone. Wilschut (2009) reported P300 effects of task load in a secondary task while participants in her driving simulator experiment performed lane-changing tasks on a simple highway. In Fig. 2 the amplitude of the P300 is different for different types of visual search on in-vehicle information displays, whereas the P300s are different for different age groups. It demonstrates additional (convergent) evidence for the problems that elderly people may experience in complex driving circumstances.

2.3. Alertness monitoring

The standard indicator for the level of alertness is the activity pattern in the EEG (see also Lammers et al., 2005). Most applications in alertness or vigilance research note the changes that follow in the usual frequency bands of the EEG during wakefulness, such as beta, alpha, and theta. However, as mentioned before, measuring EEG, even in simulator environments, is relatively demanding and expensive. Facial muscle tone and activity can also serve to measure effort and emotional strain (Van Boxtel and Jessurun, 1993), whereas position and eyelid activity can be used to detect sleepiness as well (see Åkerstedt, 2004). However, in driving simulators some easily derived measures of ocular psychophysiology have great potential to detect minute-to-minute changes in drowsiness and hypo-vigilance associated with lapses of attention during performance very well. Specifically a measure of slow eyelid closure, labelled as percentage of closure or PERCLOS (Wierwille et al., 1994; Wierwille and Ellsworth, 1994), correlates highly with visual vigilance performance lapses (Dinges et al., 1998; Mallis and Dinges, 2004). PERCLOS is implemented by video-based scoring of slow eyelid closures, and correlates even better to performance decrement than the participant's own ratings of their sleepiness (Mallis and Dinges, 2004). PERCLOS has the potential to detect fatigue-induced lapses of attention during task performance, certainly in the relatively protected simulator environment, in particular as soon as the PERCLOS scoring algorithm used by human observers in laboratory studies is automated in a computer algorithm, interfaced to provide informational feedback on alertness and drowsiness levels and scientifically validated in a controlled laboratory experiment. PERCLOS is technically ready for implementation in real world driving, especially useful in situations such as long distance driving. However, relevant barriers are still issues like liability in case of failure and complacency by the driver (see Brookhuis et al., 2003b).

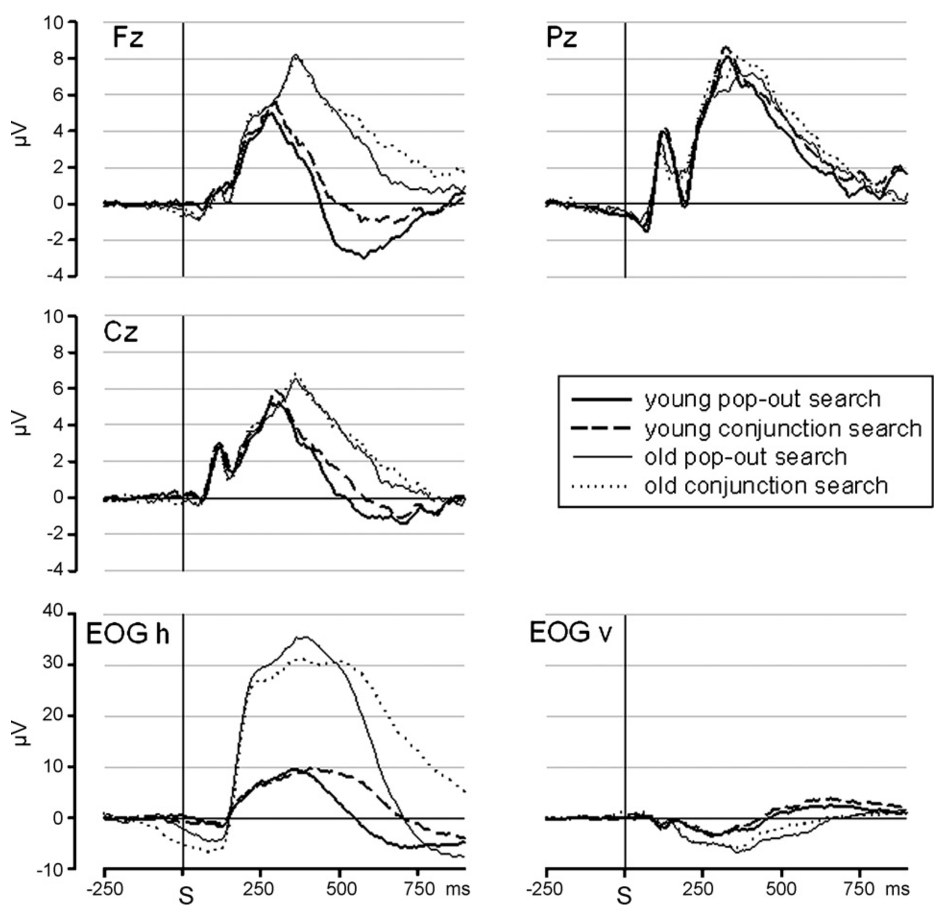

Fig. 2. Grand-average ERPs time-locked to the visual search stimuli, for two age-groups, for pop-out versus conjunction search, for Fz, Cz and Pz and the uncorrected EOG channels. The ERPs are elicited in response to discrete stimuli of a secondary task while driving in a simulator (primary task). Note that the EEG channels have a different scaling than the EOG channels (from Wilschut, 2009).

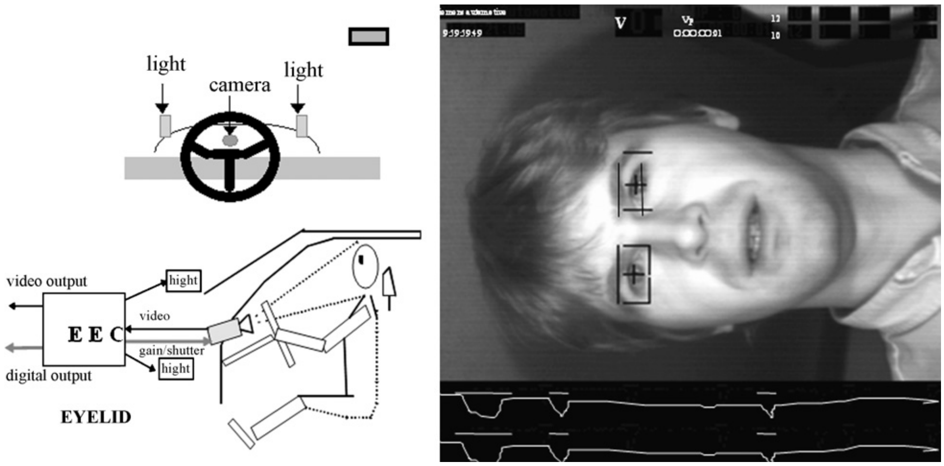

Fig. 3. Example of a set-up to measure eye-blinks (left) and the resulting output (right), with clearly different lengths of the three displayed blinks (bottom white lines), with increasing durations from right to left (from Brouwer et al., 2004).

In Fig. 3 an illustrative picture is given from a simulator experiment in an EU-project concerning the development of driver vigilance monitoring equipment (Brouwer et al., 2004).

3. Conclusions

Driver mental workload should be optimal, i.e. not too high, not too low, to ensure adequate driving performance. Research in the field is difficult and often ethically unacceptable if not impossible at all on the road itself. Therefore, advanced driving simulators are in fact profitable to us in two ways; they enable to study realistic conditions, without any objective risks, while at the same time they function as clean laboratories, equivalent with cognitive psychology laboratories. The preconditions that are necessary for human (psycho)-physiological measurements to monitor driver mental workload are relatively easily fulfilled, although we hasten to say that considerable skills with respect to programming and measuring physiology are among the basic requirements. A number of delicate psycho-physiological experiments have already been conducted in driving simulators, while new directions like neuropsychological research with advanced methods such as fMRI (functional Magnetic Resonance Imaging) may still seem (almost) impossible but is within reach when the simulator can be brought to the MRI equipment. Calhoun et al. (2004) have investigated effects of alcohol intoxication by means of a simple driving simulator setup and demonstrated that fMRI can be applied in this way. Technology in both fields is developing at a great pace, enabling opportunities to bring them together more easily in the near future.

The added value of being able to “look into the driver's body”, monitoring a participant's capabilities in driving simulator experiments is not very common yet, but will quickly expand, is our conviction. The use of physiological measures is a promise for capturing mental workload in simulator driving studies.

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