Measuring Driver's Mental Workload Using EEG

According to analyses of traffic accident data, 90 % of traffic accidents are caused by driving failures due to an impaired driver mental state [1, 2]. The development of optimal Advanced Driver Assistance Systems (ADAS) requires a profound understanding of the causes and factors that lead to an impaired driver mental state, such as fatigue, inattention or mental overload. However, the interaction of driver, vehicle and environment is extremely complex and the traditional analytical methods of behavioral psychology are often insufficient and difficult to assess. Using EEG, the Daimler AG has brought neurophysiological approaches from the laboratory into the vehicle and is able to perform real-world driving studies.

1 Introduction

Modern neuroimaging techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), multichannel electroencephalography (EEG) or magnetoencephalography (MEG), and near infrared spectroscopic imaging (NIRSI) enable the study of the neural basis of human behavior and cognition, thus making it possible to establish an effective and objective measurement procedure for the mental state. Using EEG, we have brought this approach from the laboratory into the vehicle, which allows us to perform real-world driving. These findings have a high validity and are more applicable to the actual environment, thus contributing significantly to the improvement of vehicle and traffic safety.

2 Mental Load in Automotive Environments

Vehicle operation is a classic example of a man-machine system involves the interaction e.g. between driver and car under aspects of exchange of information and regulatory requirements [3]. Three main components interplay in this man-machine-interaction: the driver, the vehicle and the environment [4]. The primary task of driving can be described on three behavioral levels:

1. strategic, i.e. decisions about the goal of the drive
2. tactical, i.e. immediate decisions such as choosing a driving maneuver, speed or driving lane
3. the sensory-motor control level [5], i.e. longitudinal and lateral control.

Keeping the car on the road is a highly automated skill, but in a critical situation a conscious interference is necessary e.g. to avoid a sudden obstacle on the road. If the driver is in an impaired mental state, for instance experiencing high mental workload and hence being unable to react, an accident may be the result.

Despite its extensive use, there is neither a common understanding of the term workload nor a shared methodology for measuring it, especially in connection with driving. Historically, the concept of "mental workload" was first introduced in the 1940s within the context of optimizing human-machine systems (e.g., [6]). Subsequent research led to the notion of a limited amount of mental resources as a central concept for mental workload which became the underlying concept for all subsequent models [7].

Some models differentiate between a conscious and an unconscious level of control in human information processing [8], whereas others distinguish between automatic and controlled processing [9]. Accordingly, a driver with a considerable amount of driving experience will be able to automatically control a vehicle while also directing resources to secondary tasks. By definition, automatic processing tends to be rigid and allows only limited deliberate correction on the part of the driver. Conscious and intentionally controlled processing, on the other hand, is slow and takes up a much larger amount of processing resources.

Wickens expanded on the concept of limited mental resources by incorporating qualitatively different types of mental resources and has been rewarded wide recognition [10]. His multiple resources model describes three different dimensions that are elementary to information processing:

1. the mode of information input (auditory, visual or tactile)
2. the information code (spatial or verbal)
3. the type of response (manual or vocal).

According to Wickens, conflicts arise when the same type of dimension is simultaneously addressed, e.g. a driver that talks to a passenger will have difficulty receiving the message of an incoming radio traffic report at the same time. In this situation, two pieces of information interfere with each other in the same auditory input modality. In addition, the model describes the three classic processing stages: encoding, central processing and responding. In terms of the multiple resources model, driving can be described as consisting of visual input, a spatial code, and manual output, such as steering. In contrast, a secondary task like talking to a passenger would involve auditory input, a verbal code, and vocal output. If these two tasks are performed in a parallel manner usually no conflicts are to be anticipated. An

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experienced driver can generally engage in a conversation without problem.

The models presented so far provide an understanding of how a driver is able to manage all incoming information with only a limited pool of available mental resources. Consequently, it is possible to anticipate potential conflicts in information processing channels e.g. when designing navigation systems.

3 Experimental Work on Electroencephalographic Recording under high Workload in a Real-Traffic Driving Environment

Driving is a well studied field and the driving task has been described in high detail (e.g. cf. [11] for a recent summary). Most of the studies have been performed under laboratory conditions which allow a maximum of experimental control. While using a driving simulator increases the test validity, it is uncertain if the simulated testing conditions yield results that are generally applicable in the real world. "No matter how expensive the simulator, regardless of the quality of the screen displays, a person in a driving simulator knows that they are taking part in an experiment and that it is not real [12, p. 10]"

Compared to other brain imaging techniques, EEG offers the advantage of high temporal resolution (msec) on one hand and mobility on the other. Introduced by Hanns Berger in 1929, EEG is a well established method that uses electrodes placed on the head of the subjects for measuring electrical potentials elicited by neural brain activity typically between 0 and 200 µV. The number of electrodes used is dependent on the focus of the study at hand and can range from three to more than 200.

EEG offers principally two ways to measure and quantify driver workload: indirectly, by means of event-related potentials (ERPs), and directly, by extracting EEG features from the raw EEG as direct correlates of driver workload.

4 Event-Related Potentials

Event-related potentials (ERPs) represent a characteristic brain response to a certain event such as an external stimulation or a mental operation. The elicited potential can be reliably measured by means of EEG over several repetitions. The magnitude of the ERP signal is small (5-40 µV) in comparison to the amplitude of the background EEG (0-200 µV) from which it has to be extracted. The event-locked character of the ERPs allows averaging several trials of ERPs, to obtain a better signal-to-noise ratio.

RP components are usually given labels that refer to their polarity and position within the waveform (e.g. P1 or N1) or numbers that mark their latency onset (e.g. N100, P300). In other situations the labels denote a functional description (e.g. readiness potential, RP) or refer to the brain area that is the presumed neuronal generator of the component (e.g. auditory brainstem response, ABR). A comprehensive review of ERP components and their functional meaning can be found in the books from Coles and Rugg [13] and Luck [14].

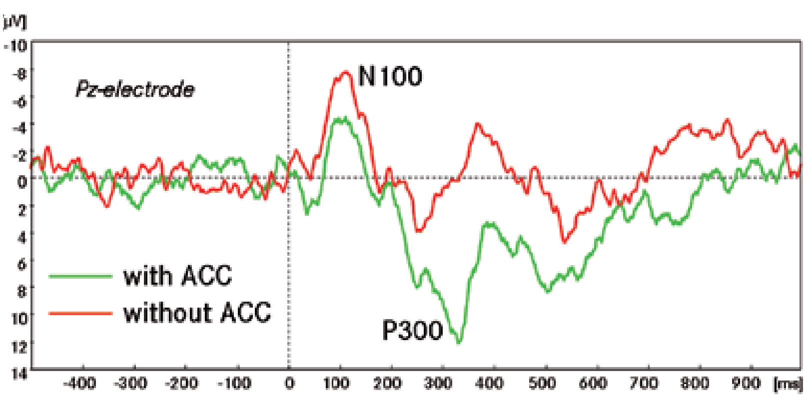

Figure 1: Example of P300 potentials evoked by an auditory stimulus during driving in two conditions: with and without active ACC.

The so-called P300 component represents a complex of visual or auditory evoked positive potentials with an amplitude typically between 5 - 40 µV occurring 300 ms after stimulus presentation. It has been suggested that besides the P300 other ERP components may provide further insights on mental workload [15]. However, since its introduction by Sutton and colleagues in 1965 [16], the P300 has become one of the most frequently measured ERP components as a measure of mental load [13].

On the basis of these studies, we assessed whether this well-established approach is suited for measuring and quantifying driver's mental workload under real driving conditions. Vehicle-based tests showed that the P300 complex was successfully elicited by a passive auditory odd-ball design in which the subjects were presented a random sequence of frequent (low pitch) and rare (high pitch) auditory tones [17]. Subsequently, two workload conditions, i.e. driving with and without adaptive cruise control (ACC), were compared in a block-design under real driving conditions. In a six hour drive on a German Autobahn, the ACC was alternately turned on and off every half hour. During the entire drive, the subjects were presented a passive auditory odd-ball task which randomly elicited P300 ERPs, every 30 seconds on average. Averaged over all trials in each of the two conditions, the analysis clearly showed a larger P300 amplitude for the condition in which the ACC was turned on, which is clear evidence for the supportive effect of the ACC, **Figure 1**.

Using ERPs such as the P300 is a very robust and reliable approach for measuring and quantifying driver workload. However, the approach does present some disadvantages. ERPs elicited by probe stimuli such as in an odd-ball design offer only a sparse, non-continuous measure of the driver's mental state. Additionally, since for signal averaging the stimuli have to be presented randomly, certain external events that might elicit a short change of driver mental load might be missed by the probe stimuli, thus not eliciting an according ERP. Nevertheless, Humphrey and Kramer [18] consider ERPs, in particular the P300, well-suited for the assessment of dynamic changes in mental workload.

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5 Continuous Measures of Driver Mental Load based on spontaneous EEG

Unlike ERPs, which offer only an indirect measure of the driver's mental load elicited by external probe stimuli, correlates of mental workload can be extracted from the spontaneous EEG activity, thus offering a continuous measure. This promises to be a more sound and substantial approach, but also far more challenging.

Numerous studies have demonstrated that with increased mental processing effort alpha waves (8–13 Hz) decrease and theta (4–8 Hz) activity is enhanced, e.g. [19, 20, 21, 22]. However, research using EEG alpha band power to study neurophysiological correlates of mental workload during driving is rare. Mental workload measurements in real operational environments have so far been reported by Sterman and Mann [23] and by Hankins and Wilson [24]. A comprehensive review of the field can be found in [25].

In a study presented in [26], we took a first step towards developing a continuous measure of driver mental load based on spontaneous EEG recordings. The study was designed such that two secondary tasks were presented in a controlled manner as subjects drove a predetermined course. The presentation of experimental stimuli and route were consistent from subject to subject, while the complexity introduced by traffic situations varied in an uncontrolled manner across experimental conditions and subjects.

One secondary task was a mental calculation task, the second one an auditory detection task. Both tasks induced mental load according to a block design in which high mental workload phases (task on) were followed by low mental workload phases (task off). The mental workload detector consisted of two parts: feature extraction and classification. Feature extraction involved artifact removal, channel selection, spatial filtering, and power computation of an individualized alpha band.

A linear model was used for classification wherein parameters were computed by standard linear discriminant analysis (LDA) of the feature vectors obtained from the high and low workload conditions of the training session [27]. Using the cross-validation technique on a training set [28], the parameter set best discriminating and generalizing between high and low mental load conditions was assessed separately for each subject. The quality of the workload detector which had a temporal resolution of 200 ms was assessed by analyzing the match between calculated detector workload and the default workload structure of the high/low block experiment design. The results showed an average detection accuracy of 70 %. However, the inter-subject variability of the detector performance was very large, ranging between 55 % and 90 %.

Especially in an open environment like real traffic driving, the consideration of individual differences and careful artifact rejection are essential to obtaining a good signal to noise ratio. Wilson and Fisher [29] used topographical information about the EEG to classify fourteen different mental tasks and thus showed that the use of individual subject EEG patterns had a great advantage over the use of group derived bands. Especially the EEG alpha band has been shown to hold an individually unique signature that may vary with age, memory performance and attentional demands [30].

Our current research demonstrated that mental workload detection based on spontaneous EEG recordings is possible with a high temporal resolution; furthermore, it allows a differentiation between different types of mental load, i.e. mental calculation and auditory attention. These results represent a first step towards developing robust, generally applicable and reliable mental workload detectors with high temporal resolution. Further research in the domain of neurophysiology, signal analysis and machine learning is necessary.

Ultimately, the effort will culminate in a commonly applicable approach that will enable us to detect traffic situations that cause high driver workload, thus improving the development of specific driver assistance systems to support the driver. Additionally, it will be possible to quantify the benefit of driver assistance systems in early development stages.

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