Accident Analysis and Prevention 91 (2016) 157–165

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Driver state examination—Treading new paths

Edmund Wascher, Stephan Getzmann*, Melanie Karthaus

IfADo—Leibniz Research Centre for Working Environment and Human Factors, Dortmund, Germany

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form 26 February 2016
Accepted 27 February 2016
Available online 14 March 2016

Keywords:
Car driving
Mental fatigue
Alpha and Theta power
EEG synchronization
Mismatch negativity

ABSTRACT

A large proportion of crashes in road driving can be attributed to driver fatigue. Several types of fatigue are discussed, comprising sleep-related fatigue, active task-related fatigue (as a consequence of workload in demanding driving situations) as well as passive task-related fatigue (as related to monotonous driving situations). The present study investigated actual states of fatigue in a monotonous driving situation, using EEG measures and a long-lasting driving simulation experiment, in which drivers had to keep the vehicle on track by compensating crosswind of different strength. Performance data and electrophysiological correlates of mental fatigue (EEG Alpha and Theta power, Inter Trial Coherence (ITC), and auditory event-related potentials to short sound stimuli) were analyzed. Driving errors and driving lane variability increased with time on task and with increasing crosswind. The posterior Alpha and Theta power also increased with time on task, but decreased with stronger crosswind. The P3a to sound stimuli decreased with time on task when the crosswind was weak, but remained stable when the crosswind was strong. The analysis of ITC revealed less frontal Alpha and Theta band synchronization with time on task, but no effect of crosswind. The results suggest that Alpha power in monotonous driving situations reflects boredom or attentional withdrawal due to monotony rather than the decline of processing abilities as a consequence of high mental effort. A more valid indicator of declining mental resources with increasing time on task seems to be provided by brain oscillatory synchronization measures and event-related activity.

1. Introduction

States of reduced wakefulness represent a severe risk of accidents in many fields of work (e.g. reviews by Williamson et al., 2011 or Rosekind et al., 1996). In particular, fatigue during road driving is a serious problem in transportation systems and is assumed to cause a large proportion of accidents (Gander et al., 1993; Lal and Craig, 2001). Detecting and specifying this state of mental decline and the attempt to develop countermeasures are therefore important issues in applied research. In the present study, we intend to specify EEG parameters that have been assigned to mental fatigue with respect to their functional meaning.

May and Baldwin (2009) distinguished between three types of driver fatigue: (a) sleep-related fatigue due to circadian rhythms and to disturbances in sleep (or rest) behavior, (b) active task-related fatigue as a consequence of demanding driving situations, and (c) passive task-related fatigue due to monotony caused by extended driving periods or automation (see also Schmidt et al., 2011; Schmidt et al., 2009; Phipps-Nelson et al., 2011; Matthews and Desmond, 2002). The latter type, often termed as "mental fatigue", becomes increasingly important due to increasing autonomy and assisting systems in vehicles.

Mental fatigue has well-documented consequences on cognitive capabilities. Numerous studies investigated changes of cognitive functions with time on task, demonstrating that mental fatigue mainly leads to a decline in working memory capacity and focusing attention (this refers to experimental studies that measured processing of monotonous stimuli apart from driving). Mental fatigue provokes lapses and distraction in information processing that result in inadequate behavior (e.g. Peiris et al., 2006; Boksem et al., 2005; Lorist et al., 2000). Moreover, it has been demonstrated that mental underload due to monotonous tasks appears to play a central role for mental fatigue, rather than the consumption of resources, as it is the case for muscle fatigue (Larue et al., 2011; Thiffault and Bergeron, 2003). Thus, mental fatigue has been defined as the unwillingness of alert, motivated subjects to continue to perform mental work (Brown, 1994).

Neurophysiologically, mental fatigue has been related to the dopaminergic motivation system, because the effect of mental

---

* Corresponding author at: IfADo—Leibniz Research Centre for Working Environment and Human Factors, Ardeystr. 67, D-44139 Dortmund, Germany. Fax: +49 2311084401.
E-mail address: getzmann@ifado.de (S. Getzmann).

http://dx.doi.org/10.1016/j.aap.2016.02.029

fatigue can be easily reversed, for example, by increased extrinsic motivation (Boksem et al., 2006; Bonnefond et al., 2011), by short breaks from the task (Helton and Russell, 2015; Neri et al., 2002), or by the announcement that the experiment is approaching the end (Wascher et al., 2014a,b). Similarly, in applied contexts it has been reported that motivation or short verbal interaction (Schmidt et al., 2011), enhanced environmental stimulation (Thiffault and Bergeron, 2003), or even short uninformative tone bursts as arousing feedback (Huang et al., 2012) may decrease mental fatigue essentially. Despite, or rather because of, the motivational character of mental fatigue, people tend to misjudge their vigilance state and underestimate the extent of mental fatigue (Schmidt et al., 2009).

As outlined above, mental fatigue due to monotony is an obvious hazard in piloting, e.g., when truck or train drivers have to follow a barely changing track for hours. In order to avoid accidents, mental fatigue ought to be detected long before behavioral failures are visible. Attempts to provide reliable measures or even countermeasures for this phenomenon have a long history in applied psychology (for an overview see, e.g., Borghini et al., 2014; Lal and Craig, 2001). For this purpose psychophysiological measures are of particular interest (at least in a laboratory context), because they provide physiological responses to psychological changes without affecting the actual task of the observed person (Jap et al., 2011; Larue et al., 2011; Papadelis et al., 2007; Parasuraman, 2003).

The majority of the previous studies focused on frequency based analysis of the EEG. Even single channel measures have been shown to give reliable data for the evaluation of drowsiness (Picot et al., 2008), with activity in the Alpha, Theta, and Beta band and their combinations (Jap et al., 2011) appearing as the most promising measures (Lal and Craig, 2001; Borghini et al., 2012). However, there arise some pitfalls with this approach that have to be addressed when considering driver fatigue evaluation.

It has been reported that the EEG frequencies shift toward lower bands (Delta, Theta, Alpha) with mental fatigue (Cajochen et al., 1995; Lal and Craig, 2002; Zhao et al., 2012), while higher frequencies (Beta, Gamma) decrease in amplitude (Lal and Craig, 2002). This change in spectral distribution is assumed to reflect a reduced level of arousal and alertness (Makeig and Inlow, 1993; Makeig and Jung, 1995; Tops and Boksem, 2010). However, other studies showed increasing frontal Theta, but decreasing posterior Alpha activity in distinct stages from wake to sleep (Hori et al., 1991; Klimesch, 1999; Tanaka et al., 1997). Although it has been shown that increased Alpha activity is related to mental states in which errors become more probable (Jap et al., 2011; Ogilvie et al., 1991), a continuous increase of Alpha activity has not been observed, not even in long lasting experiments (Wascher et al., 2014a,b). With continuous measurements it has been shown that only Theta power increases continuously in extended tasks (Wascher et al., 2014a,b; Finelli et al., 2000; Hoedlmoser et al., 2011), a measure that has also been consistently reported to co-vary with performance.

Approaches trying to combine the power in several frequency bands into combined measures face some other conceptual limitations. By calculating the sum of Alpha and Theta activity divided by the sum of Alpha and Beta activity across different electrode sites, more reliable markers of mental fatigue can be obtained (Jap et al., 2011). However, given the differences in changes over time across frequency bands and topographic specificity, the simple combination does not always seem to be an adequate method. Moreover, different frequency bands may reflect different specific aspects of mental fatigue, and any combination of frequency bands is therefore prone to mix them up.

Alternatively, phasic aspects of cortical oscillations may deliver additional information about the efficiency of neural processing. It is well known that cortical oscillations across all frequency bands synchronize with events (Makeig et al., 2002). Such phase resetting is essential for efficient stimulus processing. To examine this cortical phase synchrony between cortical oscillations and events across trials the inter-trial coherence (ITC) of frequency bands (or phase locking factors) is a well-suitable measure. Synchronized neural activity in cortical networks reflects neural mechanisms underlying perception and cognition and has been shown to correlate with behavioral aspects of information processing (Fries, 2005; VanRullen et al., 2011; for review; Uhlhaas et al., 2010). The ITC is a measure of temporal synchronization, indicating the extent of phase concentration (i.e., trial-to-trial fluctuations of brain responses) across trials. ITC values range from 0 to 1, with 0 indicating the absence of synchronization and 1 suggesting perfect synchrony. The ITC delivers reliable information about attentional distraction (Ponjavic-Conte et al., 2012) and is a valid measure of fatigue, e.g., due to sleep deprivation (Hoedlmoser et al., 2011). However, a critical issue of this measure (and of the oscillatory measures outlined above) is that they vary not only with time on task, but also with cognitive demands and other task specifics. Alpha power decreases in more complex conditions (Borghini et al., 2014; Klimesch 1999), whereas Theta rather increases (Borghini et al., 2014), e.g., with the complexity of long-term memory access (Berger et al., 2014; Gevins et al., 1997).

Finally, not all electrophysiological measures considered for the detection of mental fatigue rely on oscillatory activity. Automatic responses of the nervous system to irrelevant stimuli have also been used to test physiological responses without intervening into the driver's task. One of the best known EEG component of this type is the so-called mismatch negativity (MMN). The MMN is a fronto-central event-related brain potential (ERP) that is elicited by any discriminable change in some repetitive aspect of auditory stimulation, e.g., by rare deviant stimuli embedded in a stream of frequently presented standard stimuli (Näätänen et al., 1978; for a review, see Näätänen et al., 2007). The MMN occurs irrespective of the focus of the subject's attention and is assumed to reflect automatic context-dependent pre-attentive information processing. It has been found to decrease with increasing fatigue, indicating that mental fatigue impairs pre-attentive processing (Yang et al., 2013). Also, the MMN is smaller in amplitude and shorter in latency in drowsiness and REM sleep than in waking state (Nashida et al., 2000). However, while some studies found an increase in MMN with increasing attentional load in a visual tracking task (Yucel et al., 2005; Zhang et al., 2006), other studies did not show MMN effects of the task difficulty in a continuous visual or multiple object tracking task (Muller-Gass et al., 2007; Sculthorpe et al., 2008). The MMN is usually followed by the fronto-central P3a component that is assumed to reflect an automatic reorienting or shifting of attention (e.g., Näätänen, 1992). Thus, while the MMN rather reflects an automatic sensory detection of an unexpected (deviant) event in the auditory environment, the P3a is associated with a shift of attention toward that deviant (Horváth et al., 2008). Fatigue has been found to reduce the P3a amplitude, but only in a demanding working memory task (Massar et al., 2010). In sum, while there are numerous promising approaches to determine states of fatigue, the interplay of mental fatigue, time on task, and task demands remains still unclear.

In order to generate more insight into the specificity of neural measures of mental fatigue in a car driving situation, we investigated the interaction of mental fatigue and task complexity by means of various EEG measures providing information about the state of the driver. Task complexity was introduced in order to vary workload, which can be defined as the mental effort that an operator invests to cover task demands (Hart and Wickens, 1990; O'Donnel and Eggemeier, 1986). Task demands were varied only within the primary task (single task demand, e.g. Wickens, 2008), because it served as a tool to validate time on task effects on psychophysiological parameters. In an extended monotonous ride on a driving simulator, participants had to keep a vehicle on