Accident Analysis and Prevention 62 (2014) 110–118

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

EEG alpha spindles and prolonged brake reaction times during auditory distraction in an on-road driving study

Andreas Sonnleitner[a,f,*], Matthias Sebastian Treder[b], Michael Simon[c], Sven Willmann[d], Arne Ewald[b,e], Axel Buchner[f], Michael Schrauf[g]

[a] Fraunhofer IAO, Germany
[b] Neurotechnology Group, Technische Universität Berlin, Germany
[c] Rohde & Schwarz, Germany
[d] TZM, Germany
[e] University Medical Center Hamburg-Eppendorf, Germany
[f] Heinrich Heine University Düsseldorf, Germany
[g] Daimler AG, Germany

ARTICLE INFO

Article history:
Received 8 March 2012
Received in revised form 16 July 2013
Accepted 27 August 2013

Keywords:
Distraction
Alpha spindles
EEG
Attention
On road driving
Brake reaction times
EMG
Auditory secondary task
Car following
Classification
Time on task
Single trial analysis

ABSTRACT

Driver distraction is responsible for a substantial number of traffic accidents. This paper describes the impact of an auditory secondary task on drivers' mental states during a primary driving task. $N = 20$ participants performed the test procedure in a car following task with repeated forced braking on a non-public test track. Performance measures (provoked reaction time to brake lights) and brain activity (EEG alpha spindles) were analyzed to describe distracted drivers. Further, a classification approach was used to investigate whether alpha spindles can predict drivers' mental states.

Results show that reaction times and alpha spindle rate increased with time-on-task. Moreover, brake reaction times and alpha spindle rate were significantly higher while driving with auditory secondary task opposed to driving only. In single-trial classification, a combination of spindle parameters yielded a median classification error of about 8% in discriminating the distracted from the alert driving. Reduced driving performance (i.e., prolonged brake reaction times) during increased cognitive load is assumed to be indicated by EEG alpha spindles, enabling the quantification of driver distraction in experiments on public roads without verbally assessing the drivers' mental states.

1. Introduction

Driver distraction and inattention lead to a substantial number of traffic accidents. In 2009, 5474 people died in road accidents in the United States due to driver distraction, amounting to 16% of all fatal crashes. Additionally, 448,000 injuries where at least one form of driver distraction was noticed were registered in police crash reports (NHTSA, 2010). Natural driving studies, where drivers are monitored during everyday driving, revealed an even higher influence of driver distraction on crashes, though with a broader definition of inattention, including fatigue among other things (Klauer et al., 2006). These authors reported distraction was responsible for 78% of crashes and 65% of near-crashes for automobiles. Olson et al. (2009) found distraction a contributing factor in 71% of crashes and 46% of near-crashes for heavy trucks. These naturalistic driving studies are based mainly on video analysis, a radar system, lane tracking and vehicle data in predefined safety-critical events related to randomly chosen baselines. While this approach has a high ecological validity and apparently identifies observable distraction, it is not possible to identify internally directed attention which is also known as daydreaming or highway-hypnosis (Wertheim, 1991). A stimulus presented in the eye-field of a person heading to that stimulus is not necessarily attended and consciously perceived. This so-called "looked-but-failed-to-see" phenomenon is a major cause of accidents (Herslund and Jorgensen, 2003). Given that cognitive resources are often divided among various tasks besides that of driving, performance in processing of relevant information is not always constant. In regions over the pre-frontal and parietal cortex, decision is made about the importance of a stimulus and whether attention should be paid to it (Birbaumer and Schmidt, 2010). If the incoming distraction is rated more important than the primary driving task, then

* Corresponding author. Tel.: +49 711 970 2347.
E-mail address: andreas_sonnleitner@gmx.at (A. Sonnleitner).

0001-4575/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2013.08.026

parts of the attention resources are shifted to the current secondary task.

Neuronal processes underlying attention shifts during driving can be described with different methods. Bowyer et al. (2009) investigated the influence of a conversation while watching a driving scene using magneto-encephalography (MEG). Without conversation, higher brain activity in the visual cortex (85 ms after stimulus onset) and in the right superior parietal lobe (200–300 ms after stimulus onset) resulted in shortened reaction times to small red lights embedded in a driving scene (conversation: M = 1043 ms, SE = 65.0 ms; no conversation: M = 944 ms, SE = 48.0 ms). Reduced amplitude in brain activity and an increased mean reaction time could be seen during additional hands-free conversation, while there was no statistically significant difference in miss rates. In a companion paper, Hsieh et al. (2009) conducted a study with identical design using fMRI. They investigated a frontal-parietal network that indicates effects of conversation on visual event detection. Compared to driving only, reaction times to visual events were prolonged during covert conversation. The authors assume a top-down influence of frontal regions on the synchronization of neural processes within the two key regions of superior parietal lobe and extrastriate visual cortex.

Foxe et al. (1998) found effects of the stimulus modality in parieto-occipital activity (~10 Hz). In an intermodal selective attention paradigm, visually presented words indicated the to-be-attended modality. Participants showed a higher parieto-occipital alpha activity in preparation for anticipated auditory input compared to anticipated visual input, indicating a disengaged visual attentional system. Cooper et al. (2003) have found similar correlations between alpha activity and direction of attention. They reported significantly higher alpha amplitudes for internally than for externally directed attention.

Sonnleitner et al. (2012) also found higher alpha activity while driving with as opposed to driving without auditory secondary task (in this case in terms of alpha spindles defined as sinusoidal patterns within a widened alpha band [6–13 Hz]). A detailed description of alpha spindles including a detection scheme can be found in Simon et al. (2011). The lowest alpha spindle rate (occurrence per minute) while driving was registered during the visuomotor secondary task with the highest visual information input. It is assumed that alpha spindles indicate the intensity of visual information processing. More specifically, they are assumed to refer to the thalamo-cortical gating for incoming sensory information (Pfurtscheller, 2003) and are therefore significantly involved in facilitating selective attention (Cohen, 1993).

To determine the influence of decreased visual information processing on brake reaction times, the exact process from the flashing of the brake lights until the braking of the car has to be investigated. Burkhardt (1985) reported that it takes an average of 640 ms from when an object is fixated until the brake pedal is contacted. Muscle contraction is initiated in an interval from 220 ms (2nd percentile) through 450 ms (50th percentile) to 580 ms (98th percentile). This part of the brake reaction time should be impacted by fatigued or distracted driving. In a simulator study, Strayer et al. (2006) investigated the brake reaction times (among other things) of drunk drivers (i.e., blood alcohol concentration at 0.8% w/v) and cell phone drivers (hands-held and hands-free cell phone) in a car-following study. The mean brake reaction times in response to the braking lead car varied between 777 ms (Baseline), 779 ms (Alcohol) and 849 ms (Cell Phone). The mean separation to the lead car ranged from 26.0 m (Alcohol) via 27.4 m (Baseline) to 28.4 m (Cell Phone) with time to collision varying between 8.5 s (Baseline), 8.1 s (Cell Phone) and 8.0 s (Alcohol). While cell phone drivers had slower reactions and greater separations, intoxicated drivers showed a more aggressive driving style (i.e., they hit the brakes harder, had shorter following distances). Even if the underlying mechanisms clearly differed, the authors concluded that impairments associated with using a cell phone can be as profound as those associated with drunk driving, including a comparable risk of traffic accidents.

The aim of the present study is to identify neurophysiological correlates of driver distraction as well as the influence of distraction on reaction times to forced braking. These factors were previously investigated in a laboratory study, wherein participants performed an analogous task in a driving simulator (Sonnleitner et al., 2012). In order to maximize ecological validity, the setting was transferred to real cars on a non-public test track. A major goal of the study was to replicate these findings in this realistic driving environment.

Additionally, machine learning methods were used to investigate whether the identified neural correlates can be used to predict driver distraction on a single-trial level.

Hypotheses. Performing an auditory secondary task will result in a higher mental workload and a reduced degree of visual information processing by the driver.

(a) Therefore, *driving with an auditory secondary task* is expected to increase brake reaction times and alpha spindle rate as compared to *driving only*.
(b) With ongoing *time-on-task*, brake reaction times as well as alpha spindle rate are expected to increase due to task-related fatigue.
(c) Alpha spindle rate is expected to predict driver distraction on a single-trial level (i.e., three-minute-block).

2. Methods

2.1. Participants

In total, 25 individuals participated in this study. Five of the resulting datasets had to be excluded from further analysis due to technical problems or noisy data. Therefore, the sample consisted of 20 participants (22–53 years, mean: 29.0 years, five females). Subjects were recruited from an in-house database in which volunteers for experiments are listed. Every subject had normal or corrected-to-normal vision, reported normal hearing and had no history of psychiatric or neurological diseases. Participation was voluntary and occurred during working hours. All experimental procedures were conducted in accordance with the ethic guidelines of the Declaration of Helsinki. All assessments were performed by the same research personnel, who were well trained and had relevant experience in rehabilitation research. Data were collected anonymously. Informed consent was obtained after the task had been explained. Participants were informed they had the option to end participation in the experiment at any time without any type of penalty. Participants received a gift worth approximately € 20 for their participation.

2.2. Driving task (primary task)

The study was conducted on a non-public test track in an unused military training area in Münsingen, Germany. Participants were instructed to always prioritize the primary task and to drive in accordance with official traffic regulations. They had to drive three rounds on the test track, one round being 37 km long with varying horizontal and vertical curves. The setup consisted of two Mercedes-Benz S-Class cars: the lead car was navigated by an investigator and the following car was driven by the participant. Participants were instructed to follow the lead car at a constant distance of approximately 20 m away at a maximum speed of 60 km/h. In order to obtain a reference for the required distance, the participant's car was parked 20 m behind the lead car before the start of the experiment. The investigator in the lead vehicle initiated braking from 60 km/h to 40 km/h with an interstimulus interval of

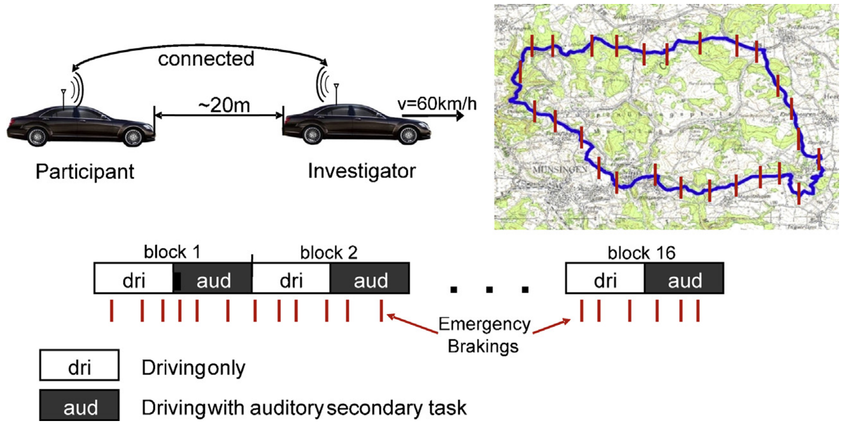

Fig. 1. Test procedure of the car following task. The participant followed the investigator in the leading car with 60 km/h at a distance of approximately 20 m for three rounds on the test track. Alternately participants drove without or with auditory secondary task.

42.5 s to 57.5 s (M = 50 s, uniformly distributed jitter) after receiving an acoustic trigger from a laptop, provided that the lead car had a constant velocity of 60 km/h and adequate separation to the trailing vehicle. As soon as the lead vehicle's braking lights came up, the participant was instructed to brake as quickly as possible, irrespective of the actual distance between the cars. After each braking event, the investigator accelerated back to 60 km/h using cruise control.

2.3. Auditory secondary task

Participants listened to parts of an audio book recording of a travelogue ("Sieben Jahre in Tibet" [Seven Years in Tibet], Harrer and Schwarz, 1952). They were instructed to alternately detect the German definite article "die" (corresponding to "the" for female nouns) or the copula "und" (engl. "and") by pressing a button on their left index finger with their thumb. In every chapter, the target words "die" and "und" appeared between 17 and 19 times each. The number of detected target words served as the performance measure.

Half of the participants additionally had to answer a question about the content of the text at the end of each interval in the second half of the experiment (order A), the other half received the question in the first half of the experiment (order B). They had to choose the correct answer out of three possible alternatives. The purpose of this question was to make sure that participants really followed the content of the audio book.

2.4. Test procedure

Before starting the experiment, participants had to complete a supervised baseline, where ocular artefacts (blinks, saccades) were recorded in order to train a method for online blink artefact correction.

For the main study, participants had to drive three rounds on the test track, with short breaks between each round which occurred after about 40 and 80 min of driving.

The experiment consisted of 16 blocks, superimposed on the continuous driving task. In every block, participants drove for 3 min without performing the auditory secondary task and for 3 min with secondary task (Fig. 1). The beginning and the end of every three-minute interval was announced verbally. Data collected during these announcements were excluded from further analysis. The driving experiment was a continuous task so that the arousal level was not influenced by breaks between blocks with the exception of the transitions at the end of each round in which sensors had to be cleaned of grime from the lead car. For the whole study, participants had to drive a total of 48 min in both conditions (*driving only, driving with auditory secondary task*).

2.5. Physiological recordings

After agreeing to the study, participants were fitted with a 32-electrode-cap (ActiCap, Brain Products GmbH, Munich). A set of 25 electrodes was positioned according to the international 10–20 system (Fig. 2). Muscle activity from the right foot was measured with two electrodes, positioned at the right musculus tibialis anterior and on the right thigh. Horizontal and vertical eye movements were measured with four electrodes. These were positioned about 2 cm above and below the right eye and at the left and right outer canthi. ECG was recorded with one electrode above the cardiac apex.

Physiological data was recorded relative to FCz and all impedances were maintained less than 10 kΩ. Data were digitized at 250 Hz with a bandpass filter (low: 0.53 Hz, high: 100 Hz) and a 50 Hz notch filter was applied to remove power line interference.

2.6. Pre-processing

EEG data was re-referenced offline to common average.

Changes in alpha spindle rate due to distraction were analyzed with a nonparametric cluster-based permutation test (Maris and Oostenveld, 2007). In this way, clusters of spatially contiguous channels can be identified without the necessity of predefined channel. T-tests for the variable distraction are calculated for each

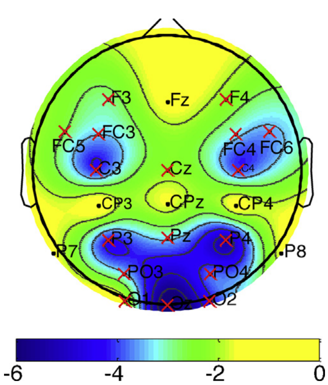

Fig. 2. Topographic plot of recorded channels. Channels for the selected cluster are marked with a red cross (17 channels). Colors represent the test statistics of t-tests between *driving with auditory secondary task* and *driving only* for each channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

channel and significant channels are concentrated on one cluster. Alpha spindle parameters of EEG-channels from the significant cluster (Fig. 2) were averaged, while EEG-channels Fz, CP3, CPz, CP4, P7, P8, T7 and T8 were excluded from further analysis.

Simon et al. (2011) reported a method based on time-frequency decomposition to automatically detect alpha spindles. Alpha spindles are short, narrow-band bursts of sinusoidal activity in the alpha band, which can be observed in spontaneous EEG recordings, especially while subjects have their eyes closed. The typical "waxing and waning" (Shaw, 2003) of the alpha rhythm leads to this burst-like structure. By defining alpha spindles as discrete events of high, narrow-band alpha power, the typical structure of the alpha rhythm can be described in terms of occurrence rate (alpha spindle rate), duration, amplitude and frequency. The algorithm searches for the individual alpha peak in a frequency band of 6–13 Hz. Time segments showing distinct alpha activity with a minimal signal-to-noise ratio (2:1) and a minimum number of four oscillation cycles are counted as spindles. As compared to the calculation of alpha band power with FFT, the extracted parameters are less susceptible to noise and adapt to the particular alpha characteristics of the subject, both in time and frequency domain.

In order to minimize the influence of muscular and technical artefacts, an artefact detection method with an auto-regression based approach was applied, similar to the method described by Schlögl (2000). Only those data segments carrying a temporal and spatial pattern resembling that of neural sources were accepted, whereas artefacts were excluded from further analysis. Alpha spindles that were detected within an artefact were not counted and the exact time period in which an artefact occurred was excluded when computing the alpha spindle rate per minute.

The time between the lead car's brake lights flashing and the brake pedal response signal from the trailing car was defined as the brake reaction time. To ensure standardized conditions for each braking, reaction times were only coded as valid when the participant had the foot on the gas pedal at the moment the lead car's brake light flashed. Response times below 200 ms and above 2 s were counted as invalid and were excluded from further analysis (0.4% of a total 2809 brake reaction times). The data was taken from the synchronized CAN signals of both the lead and the trailing car. The *distance between cars* was measured by radar and was defined as the distance to the lead car when the brake lights flashed.

The EMG signal of the musculus tibialis anterior was bipolarly deducted against the thigh. In a pre-study, this derivation provided the most reliable signals for right-foot lifting. The signal was calculated to the power of four. If the EMG signal passed a threshold of five times the preceding baseline (interval of 200 ms before the flashing of the brake lights), the time value was defined as the start of muscle movement. If the calculated time was shorter than 150 ms or longer than the calculated reaction time of the brake pedal, no numerical value was recorded.

Statistical analysis was performed using MATLAB (R2009b) including EEGLab toolbox (Delorme and Makeig, 2004) and IBM SPSS Statistics 20.

2.7. Experimental design

The experimental design was similar to the simulator study of the colleagues Haufe et al. (2011). The study implied two independent variables, *time-on-task* (16 blocks) and *distraction* (auditory secondary task, driving only). The dependent variables were EEG measures of attention (i.e., *alpha spindle rate, duration and frequency*), performance measures from the primary task (i.e., *brake reaction time, EMG reaction time and distance between cars*) and performance measures from the secondary task (correctly identified key words in the auditory secondary task).

An a priori statistical power analysis using G*Power 3.1.2 (Faul et al., 2009) showed that in order to detect differences of $f = .40$ between the two levels of the *distraction* variable given a correlation between the levels of this repeated measures variable of $\rho = .5$, a nonsphericity correction of $\varepsilon = 1.0$, and $\alpha = \beta = .05$, a total sample size of 23 was needed. A post hoc power analysis showed that given a final sample of $N = 20$, the power $(1 - \beta)$ was .92 which we consider adequate.

A repeated-measures analysis of variance (ANOVA) was used for all within-subject comparisons to identify the effect of *time-on-task* and *distraction* on each dependent measure. For *EMG reaction times*, seven datasets had to be excluded from further analysis due to missing values, and another four due to missing values for *distance between cars*. Note, however, that EMG data were used only for the analysis of the brake reaction times. Therefore, it does not have an influence on the EEG-based driver state detection which is the central focus of this study. The level of α was set to .05 for all analyses. Whenever H_0 had to be rejected, the partial η^2 is reported as a measure of relative effect size. Statistically significant results of the *distraction* variable were subjected to post hoc analysis using comparison of simple main effects by one-step Sidak (Sidak, 1971). For the *time-on-task* variable, a post hoc trend analysis was calculated using polynomial contrasts. Only significant differences and trends are reported.

For classification, the 16 blocks were split into 32 experimental blocks for each participant: 16 separate blocks for the *driving only* task and 16 blocks for the *driving with auditory secondary task*. For each three-minute block, the alpha spindle rate, frequency, amplitude and duration were extracted and used as features for classification. Regularized linear discriminant analysis (LDA) with shrinkage of the covariance matrix (Blankertz et al., 2011) was used as the classifier. For each block, the task was to predict whether the participant was engaged in *driving only* or in *driving with auditory secondary task*. The percentage of misclassified trials was taken as measure of classification performance. To this end, a leave-one-out cross-validation scheme was used (i.e., 31 out of 32 blocks were used as training data; the remaining block was used for validation). This was repeated 32 times until each block had been left out once. In each fold, the mean and variance for the alpha spindle statistic was estimated using the training data; both training and test data were normalized to zero mean and unit variance, respectively.

3. Results

3.1. Data reduction

Recall that for each participant, it was decided randomly whether participants had to answer a question about the content of the preceding audio book section in the first or in the second half of the drive. In order to test for possible differences between the two auditory secondary tasks, a paired sample t-test was calculated for every dependent variable. No significant differences were found for any of the variables (alpha spindle rate: $t\,(19) = -.423$ ns; alpha spindle duration: $t\,(19) = -.256$ ns, alpha spindle frequency: $t\,(19) = -1.121$ ns, brake reaction time: $t\,(19) = -.002$ ns). Therefore, the two variants of the auditory secondary tasks were combined into one auditory secondary task for further analysis.

3.2. Auditory secondary task

For the auditory task, participants found 70.5% of all predetermined words ("die", "und") in the text, and they could answer

Table 1
Statistical results (ANOVA for repeated measures), alpha spindle parameters and brake reaction time for the variables *time-on-task* and *distraction*.

Factor	Measure	Main effect			Trend analysis (polynomial)			
		$F(15,285)$	p	η^2	Type	F	p	η^2
Time-on-task	Spindle rate	2.270	<.01	.107	Quadratic	8.75	<.01	.315
	Spindle duration	4.429	<.001	.189	Linear	5.49	<.05	.224
	Spindle frequency	2.386	<.01	.112	Linear	8.34	<.01	.305
	Brake reaction time	9.304	<.001	.329	Linear	76.0	<.001	.800
	Muscular response	1.692	ns					
	Distance	1.164	ns					

Factor	Measure	Main effect			Pairwise comparison (Sidak)
		$F(1,19)$	p	η^2	Post hoc effect
Distraction	Spindle rate	12.407	<.01	.395	Auditory > driving
	Spindle duration	2.202	ns		
	Spindle frequency	1.928	ns		
	Brake reaction time	20.833	<.001	.523	Auditory > driving
	Muscular response	14.188	<.01	.542	Auditory > driving
	Distance	2.160	ns		

75.1% of all questions correctly. No effects of *time-on-task* could be found for the auditory secondary task.

3.3. Main results

3.3.1. EEG alpha spindle parameters

The alpha spindle rate was significantly higher when *driving with auditory secondary task* compared to *driving only* ($F(1,19) = 12.407$, $p < .01$), $\eta^2 = 395$). Polynomial trend analysis ($F(1,19) = 8.749$, $p < .01$, $\eta^2 = .315$) showed a quadratic increase in alpha spindle rate over time.

Alpha spindle duration and frequency did not differ between driving with as opposed to driving without secondary task. Polynomial trend analysis showed a significant linear increase for alpha spindle duration ($F(1,19) = 5.487$, $p < .05$, $\eta^2 = .224$) and alpha spindle frequency ($F(1,19) = 8.341$, $p < .01$, $\eta^2 = .305$). Duration increased while frequency decreased with increasing time-on-task (Table 1, Fig. 3).

3.3.2. Brake reaction times

Fig. 4 shows the brake reaction time as an indicator for driving performance. Braking was significantly slower when *driving with auditory secondary task* ($M = 803$ ms, SE = 27.7 ms) as opposed to *driving only* ($M = 728$ ms, SE = 17.6 ms; $F(1,19) = 20.833$, $p < .001$, $\eta^2 = .523$). For the *time-on-task* variable, polynomial trend analysis showed a significant linear increase with time of driving ($F(1,19) = 75.992$, $p < .001$, $\eta^2 = .800$).

Due to missing values, seven datasets had to be excluded from the analysis of *EMG reaction times*. For the remaining 13 datasets the mean reactions were significantly slower for *driving with auditory secondary task* ($M = 369$ ms, SE = 20.5 ms) than for *driving only* ($M = 305$ ms, SE = 16.3 ms; $F(1,12) = 14.188$, $p < .01$, $\eta^2 = .542$). No impact of *time-on-task* was found ($F(4.136,180) = 1.692$ ns).

Due to missing values, only 16 of 20 datasets could be analyzed for the *distance between cars* variable. The distance between the lead car and the trailing car at the moment the brake lights flashed was not significantly affected by whether an auditory secondary task had to be performed or not ($F(1,16) = 2.160$ ns). The averaged distance over the whole task was $M = 17.0$ m (SE = .68 m) for *driving only* and $M = 17.4$ m (SE = .70 m) for *driving with auditory secondary task*.

The *time-on-task* variable had no significant impact on the *distance between cars* ($F(2,174,225) = 1.164$ ns). However, participants kept a larger separation distance at the beginning (first block: $M = 18.2$ m, SE = 1.08 m) compared to the end of the drive (last block: $M = 16.1$ m, SE = .98 m), with a decrease over time independent of the variable *distraction*. A linear basic fit showed a decrease of distance of 0.15 m per block.

3.4. Classification

Classification was performed for all combinations of alpha spindle parameters (i.e., rate, amplitude, frequency and duration) and was able to discriminate between the two conditions of distraction (*driving with auditory secondary task, driving only*). Further, classification error decreased for combined multiple features. The analysis therefore focused on the feature sets comprising three and four alpha spindle parameters. The classification error for each subject and each feature set, along with means and median, is shown in Fig. 6. The combination of all four spindle parameters tended to yield the best performance of about 8% classification error.

We further found a statistically significant negative relationship between classification error and level of alpha spindle rate ($r_s(18) = -.46$, $p < .05$). In other words, classification is best for participants with a high alpha spindle rate and worst for participants with a low spindle rate. Alpha spindle rate also shows a significant positive relationship with variability of the spindle rate across trials ($r_s(18) = .92$, $p < .001$).

4. Discussion

4.1. Distraction

The results clearly show that *driving with auditory secondary task* results in longer brake reaction times compared to *driving only*. This effect was also apparent in the extracted *EMG reaction times*. Together with the finding of a higher alpha spindle rate when driving with as opposed to driving without auditory secondary task, this suggests that shifts of attention to the auditory inputs led to an inhibition of visual information processing. This fits with results reported by Cooper et al. (2003) and by Foxe et al. (1998) who also found that attentional shift affected alpha band power. In a driving simulator study (Sonnleitner et al., 2012), driving with as opposed to driving without auditory secondary task had effects on alpha spindle parameters that were essentially identical to the ones reported here. While alpha spindle rate was significantly higher during *driving with auditory secondary task* compared to *driving only*, there was no difference between these conditions in the alpha spindle duration.

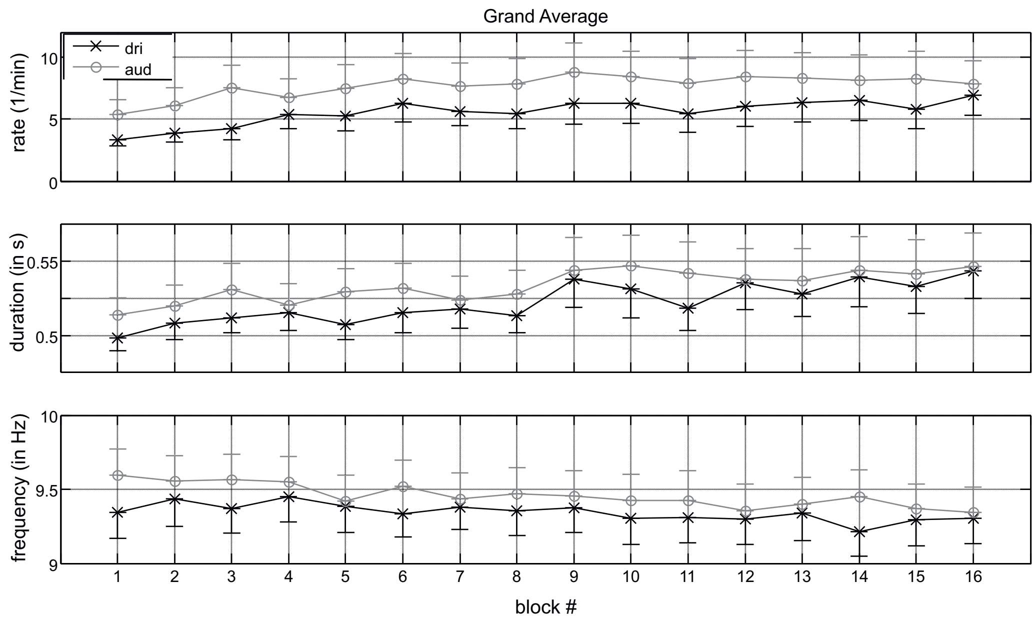

Fig. 3. Chronological sequence of alpha spindle rate (top panel), duration (centre panel), and frequency for *driving only* (dri) and *driving with auditory secondary task* (aud).

The brake reaction times reported here (M = 766 ms, SE = 21.7 ms) are similar to the ones by Burkhardt (1985), who reported an average of 640 ms from fixating an object until initiating braking. This author reports an additional interval from the appearance of the object until fixating it of 320–550 ms. In the present study, no additional distractions (i.e., other cars or pedestrians) appeared on the test track and participants were instructed to react quickly, therefore the additional time to fixate the flashing brake lights of the lead car can be assumed to be minimal.

In Fig. 5, EMG activity is illustrated for a total of 132 brake reactions of one participant. The prolonged brake reaction times can be explained by slower and less intensive muscle contractions. Mean EMG reaction time was measured at 337 ms (SE = 16.5 ms).

The 75 ms mean brake reaction time delay for *driving with auditory secondary task* compared to *driving only* is similar to the one reported by Strayer et al. (2006). In a high-fidelity driving simulator, the authors found prolonged brake reaction times for drivers who were conversing on either a handheld or hands-free cell phone (M = 849 ms, SE = 36.0 ms) compared to a baseline (M = 777 ms, SE = 33.0 ms) with a mean delay of 72 ms.

During *driving with auditory secondary task*, it is assumed that prolonged brake reaction times originate from limited cognitive resources and consequentially prolonged information processing of the flashing brake lights.

4.2. Time-on-task

Next to short-term variations in the alpha spindle rate that may indicate phasic cognitive processes (e.g., distraction from monotonous monitoring tasks like highway driving), Schmidt et al. (2009) and Simon et al. (2011) reported that fatigue had a rather long-term effect on the alpha spindle rate. In this study, strong

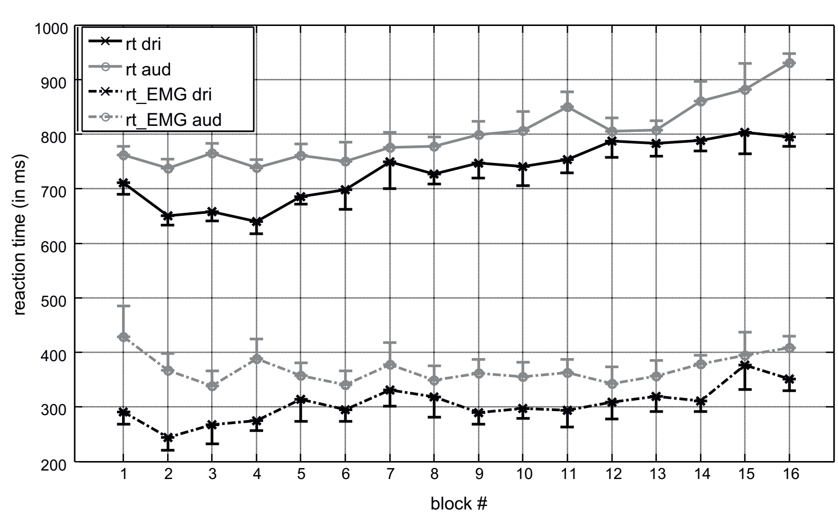

Fig. 4. Upper two curves: *brake reaction times* for conditions *driving only* (rt dri) and *driving with auditory secondary task* (rt aud); Lower two curves: *EMG reaction times* for conditions *driving only* (rt_EMG dri) and *driving with auditory secondary task* (rt_EMG aud).

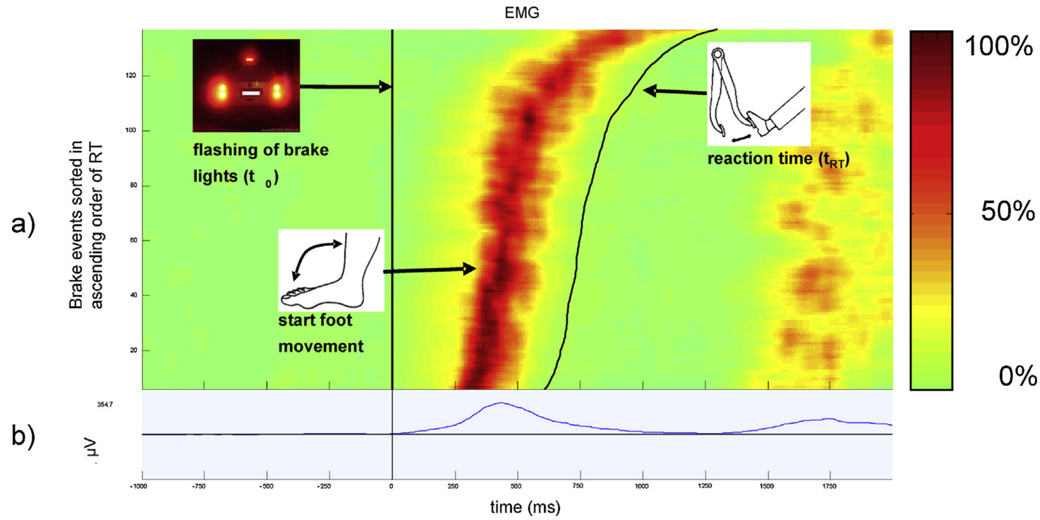

Fig. 5. Chronological sequence of the EMG intensity signal of one subject ($N = 1$) during his 132 braking events starting 1000 ms prior to the flashing of the brake lights ($t_0 = 0$ ms), and ending 2000 ms thereafter. The icons describe the action and their arrows point to the associated time. (a) Upper graph: EMG signal of 132 events sorted in ascending order (i.e. #1 the fastest, #132 the slowest) and baseline corrected to the period 1 s prior to the stimulus. The power of the EMG signal is color coded (see legend on the right) between 0% showing no muscular action and 100% representing the maximal EMG signal obtained for this subject. (b) Lower graph: shows the average of all 132 EMG brake reactions of this participant. An increase of muscle activity can be observed after about 250 ms. Participants showed another increase in EMG activity at about 1500 ms due to their right foot lift to return back to the gas pedal.

effects of *time-on-task* could also be seen in the alpha spindle rate and in the brake reaction times. Brake reaction times increased linearly while alpha spindle rate showed a quadratic increase in polynomial trend analysis. After half of the drive, a ceiling effect could be seen for the increase of alpha spindle rate (see Fig. 3). Since EMG reaction times did not significantly increase over time, longer movement duration from lifting the right foot from the gas pedal until the actual movement of the brake pedal is responsible for longer total brake reaction times. This possibly originates from a habituation effect or an emotional blunting due to task-related fatigue.

While the auditory secondary task had no effect on alpha spindle duration and frequency, both parameters showed significant effects of *time-on-task*. Alpha spindle duration increased with driving time, possibly due to longer inhibition of visual information processing from increased fatigue (Sonnleitner et al., 2012). This could be an alternative explanation of the observed ceiling effect. Longer periods of inhibited information processing appear with duration of driving at a constant alpha spindle rate.

Further, alpha spindle frequency decreased as a function of time-on-task. This indicates a frequency shift from a higher alpha activity down to theta activity, as can also be observed during the transition from waking to sleeping (Klimesch, 1999). A shift of the major frequency component below 6 Hz could result in a shift of the detected peak frequency out of the predefined alpha band (6–13 Hz) and no alpha spindles could be detected. Even if more spindles in lower frequency bands are detected, an additional widening of the predefined frequency band would increase the influence of low-frequency artefacts and would make an interpretation of received results difficult.

Since the drivers are still aware of the driving task, a minimal amount of visual information processing is still necessary to drive

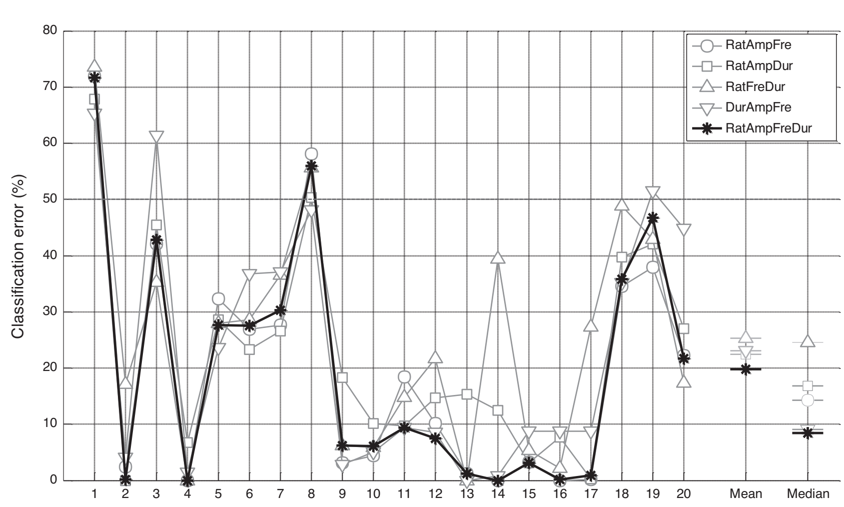

Fig. 6. Classification error for each subject and for different combinations of alpha spindle parameters. Best median performance (8% classification error) is obtained for the combination of all four parameters (asterisk). The different combinations are specified in the legend. The dashed line at 50% classification error indicates chance performance. (Rat = rate; Amp = amplitude; Fre = frequency; Dur = duration).

a car and to react to flashing brake lights. Hence, these restrictions could also be the reason for the observed ceiling effect.

4.3. Classification

Neurophysiological analysis is typically restricted to investigating effects at a group level, that is, statistics are calculated over the whole set of participants. It is instructive, however, to shed light on whether discriminability of alpha spindles regarding the driving condition also surfaces for single-subjects at a single-trial level (i.e., a single three-minute block). A machine learning approach was used to demonstrate that a driver's condition could indeed be classified at a single-trial level, with a median classification error of 8% across subjects. While the classification performance was nearly random for four subjects, good classification performance (less than 10% classification error) could be obtained for eleven subjects. This result emphasizes the robustness of alpha spindles as a sensitive indicator of distraction, albeit for a subset of subjects.

There has been some work on the classification of mental states such as cognitive workload using EEG features (e.g., Gevins et al., 1998), but few studies focussed on the classification of mental states during car driving with EEG parameters. Kohlmorgen et al. (2007) performed a real-time classification of mental workload under real traffic conditions. While driving a car on a German highway, participants had to perform additional auditory and/or mental calculation tasks. Two different levels of workload were induced by having participants perform either one or two additional tasks while driving. The classification approach focused on the modulation of oscillatory brain activity in the delta, theta, and alpha bands, operationalized as spectral parameters obtained from a 10 s EEG segment. Kohlmorgen et al. reported a high variability of classification performance across participants with perfect or near-perfect classification for many participants. This dovetails nicely with the present study, where a high inter-subject variability was found using spindle parameters with perfect performance in a subset of participants.

We showed that these individual differences in classification are related to the level and the variability of alpha spindle rate. In general, classification error was low for participants with a high alpha spindle rate accompanying a higher variability, and high for participants with a lower alpha spindle rate. Individual differences across participants regarding alpha rhythm and alpha peak are well-known in the literature (Niedermeyer, 1999) and a higher level of alpha spindle rate goes along with a higher sensitivity to changes in mental state.

5. Conclusion

The results of the present car-following study on a non-public test track show a significant increase in brake reaction times, EMG reaction times, and alpha spindles for driving with auditory secondary task compared to *driving only*. Auditory distraction leads to an internalization of attention and therefore reduced visual information processing, indicated by an increased alpha spindle rate. Time-on-task also has a significant influence on alpha spindle rate and brake reaction times. In the EMG, no statistically significant effects could be found for *time-on-task* which can be better explained by slower foot movement due to emotional blunting towards the end of the experiment than by increased fatigue after two hours of driving.

EEG alpha spindles proved to be suitable for the quantification of driver distraction in real road driving without verbally assessing the drivers' mental states. A classification approach showed the ability of spindle parameters to classify two conditions *driving with auditory secondary task* and *driving only* in a single-trial analysis with a classification error of about 8%.

Acknowledgements

This research was supported by BMBF (German Federal Ministry of Education and Research) Grant 01IB08001E. We thank members of the "Brain at Work" project in Berlin for valuable discussions on the experimental design and the interpretation of results.

References

Birbaumer, N., Schmidt, R.F. (Eds.), 2010. Biologische Psychologie (7., vollst. überarb. u. ergänzte Aufl.). Springer-Lehrbuch, Springer Medizin, Heidelberg.

Blankertz, B., Lemm, S., Treder, M., Haufe, S., Müller, K.-R., 2011. Single-trial analysis and classification of ERP components – A tutorial. NeuroImage 56 (2), 814–825.

Bowyer, S.M., Hsieh, L., Moran, J.E., Young, R.A., Manoharan, A., Liao C.-c., J., Malladi, K., Yu, Y.-J., Chiang, Y.-R., Tepley, N., 2009. Conversation effects on neural mechanisms underlying reaction time to visual events while viewing a driving scene using MEG. Brain Research 1251, 151–161.

Burkhardt, M., 1985. Reaktionszeiten bei Notbremsvorgängen. Verlag TÜV Rheinland, Köln.

Cohen, R.A., 1993. The Neuropsychology of Attention. Critical Issues in Neuropsychology. Plenum Press, New York.

Cooper, N.R., Croft, R.J., Dominey, S.J.J., Burgess, A.P., Gruzelier, J.H., 2003. Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. International Journal of Psychophysiology 47 (1), 65–74.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods 134 (1), 9–21.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.G., 2009. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behavior Research Methods 41 (4), 1149–1160.

Foxe, J., Simpson, G., Ahlfors, S., 1998. Parieto-occipital ∼10 Hz activity reflects anticipatory state of visual attention mechanisms. NeuroReport 9 (17), 3929–3933.

Gevins, A., Smith, M.E., Leong, H., McEvoy, L., Whitfield, S., Du, R., Rush, G., 1998. Monitoring working memory load during computer-based tasks with EEG pattern recognition methods. Human Factors: The Journal of the Human Factors and Ergonomics Society 40 (1), 79–91.

Haufe, S., Treder, M.S., Gugler, M.F., Sagebaum, M., Curio, G., Blankertz, B., 2011. EEG potentials predict upcoming emergency brakings during simulated driving. Journal of Neural Engineering 8 (5), 056001.

Harrer, H., Schwarz (Speaker), M.M., 1952. Sieben Jahre in Tibet [CD]. Verlag und Studio für Hörbuchproduktionen, Marburg.

Herslund, M.-B., Jorgensen, N.O., 2003. Looked-but-failed-to-see-errors in traffic. Accident Analysis and Prevention 35 (6), 885–891.

Hsieh, L., Young, R.A., Bowyer, S.M., Moran, J.E., Genik, R.J., Green, I.I., Chiang, C.C., Yu, Y.-R., Liao, Y.-J., Seaman, C.-C.S., 2009. Conversation effects on neural mechanisms underlying reaction time to visual events while viewing a driving scene: fMRI analysis and asynchrony model. Brain Research 1251, 162–175.

Klauer, S.G., Dingus, T.A., Neale, V.L., Sudweeks, J.D., Ramsey, D.J., 2006. The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data (Report No. DOT HS 810 594). National Highway Traffic Safety Administration, USDOT, Washington, DC.

Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Research Reviews 29, 169–195.

Kohlmorgen, J., Dornhege, G., Braun, M., Blankertz, B., Müller, K.-R., Curio, G., Hagemann, K., Bruns, A., Schrauf, M., Kincses, W.E., 2007. Improving human performance in a real operating environment through real-time mental workload detection. In: Dornhege, G., Millán, d.R., Hinterberger, T., McFarland, D., Müller, K.-R. (Eds.), Toward Brain-Computer Interfacing. MIT press, Cambrige, MA, pp. 409–442.

Maris, E., Oostenveld, R., 2007. Nonparametric statistical testing of EEG- and MEG-data. Journal of Neuroscience Methods 164 (1), 177–190.

NHTSA, 2010. Distracted Driving 2009 (DOT HS 811 379). National Highway Traffic Safety Administration, Washington, DC, Retrieved from http://www.distraction.gov/files/dot/6835_DriverDistractionPlan_4-14_v6_tag.pdf

Niedermeyer, E., 1999. The normal EEG of the waking adult. In: Niedermeyer, E., Lopes da Silva, F. (Eds.), Electroencephalography: Basic Principles, Clinical Applications, and Related Fields. Williams and Wilkins, Baltimore, pp. 149–173.

Olson, R.L., Hanowski, R.J., Hickman, J.S., Bocanegra, J., 2009. Driver Distraction in Commercial Vehicle Operations. (Document no. FMCSA-RRT-09-042). Federal Motor Carrier Safety Administration, USDOT, Washington, DC.

Pfurtscheller, G., 2003. Induced oscillations in the alpha band: functional meaning. Epilepsia 44, 2–8.

Schlögl, A., 2000. The Electroencephalogram and the adaptive Autoregressive Model: Theory and Applications. Shaker Verlag, Aachen.

Schmidt, E.A., Schrauf, M., Simon, M., Fritzsche, M., Buchner, A., Kincses, W.E., 2009. Drivers' misjudgement of vigilance state during prolonged monotonous daytime driving. Accident Analysis and Prevention 41 (5), 1087–1093.

Shaw, J.C., 2003. The Brain's Alpha Rhythms and The mind. Elsevier, New York.

Sidak, Z., 1971. On probabilities of rectangles in multivariate Student distributions: their dependence on correlations. Annals of Mathematical Statistics 42 (1), 169–175.

Simon, M., Schmidt, E.A., Kincses, W.E., Fritzsche, M., Bruns, A., Aufmuth, C., Bogdan, M., Rosenstiel, W., Schrauf, M., 2011. EEG alpha spindle measures as indicators of driver fatigue under real traffic conditions. Clinical Neurophysiology 122 (6), 1168–1178.

Sonnleitner, A., Simon, M., Kincses, W.E., Buchner, A., Schrauf, M., 2012. Alpha spindles as neurophysiological correlates indicating attentional shift in a simulated driving task. International Journal of Psychophysiology 83 (1), 110–118.

Strayer, D.L., Drews, F.A., Crouch, D.J., 2006. A comparison of the cell phone driver and the drunk driver. Human Factors: The Journal of the Human Factors and Ergonomics Society 48 (2), 381–391.

Wertheim, A.H., 1991. Highway hypnosis: a theoretical analysis. In: Gale, A.G., Brown, I., Haslegrave, C.M., Moorhead, I., Taylor, S.P. (Eds.), Vision in Vehicles III. Elsevier, North-Holland, pp. 467–472.