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Alpha spindles as neurophysiological correlates indicating attentional shift in a simulated driving task

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ABSTRACT

The intention of this paper is to describe neurophysiological correlates of driver distraction with highly robust parameters in the EEG (i.e. alpha spindles). In a simulated driving task with two different secondary tasks (i.e. visuomotor, auditory), $N=28$ participants had to perform full stop brakes reacting to appearing stop signs and red traffic lights. Alpha spindle rate was significantly higher during an auditory secondary task and significantly lower during a visuomotor secondary task as compared to driving only. Alpha spindle duration was significantly shortened during a visuomotor secondary task. The results are consistent with the assumption that alpha spindles indicate active inhibition of visual information processing.

Effects on the alpha spindles while performing secondary tasks on top of the driving task indicate attentional shift according to the task modality. As compared to alpha band power, both the measures of alpha spindle rate and alpha spindle duration were less vulnerable to artifacts and the effect sizes were larger, allowing for a more accurate description of the current driver state.

1. Introduction

1.1. Alpha band activity

Traditionally the alpha activity in the EEG was thought to reflect general cortical idling (Berger, 1929). As for the functional significance of the alpha component, Mann et al. (1996) observed a decrease in occipital alpha band power during visual stimulation and scanning tasks and Pfurtscheller et al. (1996) reported a task-related decrease of alpha band power over sensorimotor areas during visual processing or foot movement (μ-rhythm).

However, several findings are incompatible with the assumption of alpha reflecting cortical idling leading some to conclude that alpha band oscillations represent active inhibition irrespective of the direction of attention (Ray and Cole, 1985) or the active inhibition of sensory information in task-irrelevant cortical areas (Jokisch and Jensen, 2007; Klimesch et al., 2007).

Ray and Cole (1985) also reported that alpha and low beta activity is more sensitive to attentional demands especially in the parietal areas and is only weakly represented in the frontal areas. Cooper et al. (2003) found a clear relationship between alpha and both direction of attention (external and internal) and increased task demands. Alpha band power was higher during internally directed attention and during increased workload at various scalp sites. Klimesch (1999) suggested that event-related desynchronisation (ERD) in the lower alpha band (6–10 Hz) can be obtained in response to a variety of non-task-specific factors. It is topographically widespread over the scalp and reflects more general task demands and attentional processes. Foxe et al. (1998) suggested that ~10 Hz oscillations in parieto-occipital areas are affected by the direction and maintenance of visual or auditory attention. Participants had to do an intermodal selective attention task where word cues were visually presented. They showed a higher parieto-occipital ~10 Hz activity in preparation for anticipated auditory input as compared to visual input which reflects a disengaged visual attentional system while focusing on auditory input. This fits to Birbaumer and Schmidt (2006) who reported that afferents and efferents of the prefrontal cortex anatomically select momentarily important parts of gathered information, i.e. only acoustic information can pass via medial geniculate nucleus. The interaction between the thalamus and the cerebral cortex, which are widely and complexly interconnected anatomically, phylogenetically and functionally (Reinoso-Suárez et al., 2011), plays an important part in shifting attention.

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A different approach to measure alpha activity has been proposed by Simon et al. (2011). The authors reported a method to automatically detect so-called alpha spindles and analyzed several properties of this EEG component. Driver fatigue had a long-term effect on the alpha spindle rate (occurrence rate per minute), but there were also short-term variations, indicating additional influences of other cognitive processes. Even though alpha activity is partially generated in the cortex (Bollimunta et al., 2011), alpha spindles are assumed to be largely controlled by the interplay between thalamic relay cells and the thalamic reticular nucleus, as well as thalamo-cortical interactions. This thalamo-cortical gating serves as a relay for incoming information and values information by acting as an integration system for the transfer of sensory information (Pfurtscheller, 2003). Adjusting attention by projecting arousal from reticular activation to specific cortical processing systems plays an important role for the process of selective attention (Cohen, 1993). These selection mechanisms weight information coming from different modalities, depending on the attended stimuli. Therefore, alpha activity, in particular alpha spindles, might serve as an indicator of the current attentional focus.

1.2. Gamma band activity

Previous studies reported that EEG activity in the gamma band can be modulated by attention. Landau et al. (2007) showed that voluntary shifts of spatial attention are linked to a gamma-band response. Fell et al. (2003) also reported findings indicating synchronized gamma activity to be involved in selective attention. Jensen et al. (2007) noted that human gamma-frequency oscillations play an important role in neuronal communication and synaptic plasticity and therefore are associated with attention and memory processes. Gruber et al. (1999) reported higher power in a lower gamma band (35–51 Hz) on parieto-occipital electrode sites contralateral to an attended rotating stimulus. When shifting attention to the left or to the right the lower gamma band response changed from a broad posterior distribution to an increase of power only at contralateral parieto-occipital sites. Generally, gamma band power increased for subjects attending to a certain stimulus as compared to ignoring the same stimulus (Müller et al., 2000). These findings support the idea that induced gamma band activity is closely related to visual information processing and attentional perceptual mechanisms.

However, results from the above described studies mostly rely on experiments with little ecological validity, since they often depict isolated stimuli out of complex scenarios. It remains open whether these results can be replicated in a more realistic setting such as performing in a simulated driving task with less controlled conditions and possibly more influences of noise and artifacts.

1.3. Hypothesis

The aim of this study is to identify correlates of inattentive driver states that are induced by executing secondary tasks. These mental states are described by EEG parameters that are robust to ocular, muscular and technical artifacts which typically occur during driving.

Alpha spindle rate and *alpha band power* are expected (a) to increase while performing on an auditory secondary task indicating inhibited visual information processing and (b) to decrease while performing on a visuomotor secondary task indicating increased visual information processing. *Gamma band power* should increase during the visuomotor secondary task indicating a higher level of visual information processing.

2. Methods

2.1. Participants

A total of 29 employees participated in this study (20–42 years, mean: 28.0 years), 17 male and 12 female. A subgroup of 20 participants had no experience in driving simulators. 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 time. All experimental procedures were conducted in accordance with the ethic guidelines of the German Psychological Society (Deutsche Gesellschaft für Psychologie) and the German Psychologists' Professional Association (Berufsverband deutscher Psychologen) from 1998. All assessments were performed by the same research personnel, who were well trained and had relevant experience in rehabilitation research. Subjects were recruited from an in-house database, in which voluntary participants are listed for experiments. Data were collected anonymously. Informed consent was obtained after the task had been explained. Participants were informed that they could stop participating in the experiment at any time without any monetary or other penalties. For participation they received compensation in form of a gift worth approximately € 10.

Due to technical problems one dataset had to be excluded from further analysis; in total 28 datasets were statistically analyzed.

2.2. Simulator

The study was conducted in a simulator localized in a laboratory at Daimler AG in Sindelfingen, Germany. The simulator was rebuilt from a Mercedes-Benz C-Class (type W203, automatic transmission) that created a natural environment with a conventional brake and accelerator pedal, a steering wheel, a complete dashboard and an adjustable car seat position. The driving task was coded with STISIM Drive V2.0 (Systems Technology Inc.). The driving scene was projected by an Epson EMP7800 on a 2.05 m × 1.05 m screen 1.00 m above the ground in 1.95 m distance from the seat.

2.3. Driving task (primary task)

Participants were instructed to always prioritize the primary task and drive in accordance to official traffic regulations. The maximum speed of the vehicle was 100 km/h (~60 mph) and the difficulty of the course was very low, so participants could easily follow the street. They drove about 80 km (two rounds of 40 km) interrupted by a short break after the first round. This driving task lasted about 60 min and was subdivided into two sets of three different blocks, one set for each round. In each of the total six blocks participants had to react to critical situations (red traffic lights, stop signs). A stop sign suddenly appeared over the entire screen, while the traffic light was announced by a sign 800 m earlier and could be seen 400 m before arriving. It turned to red four seconds before the driver would have passed the stop line with the current speed.

In each block four traffic lights (two of them turned red, two stayed green) and four stop signs appeared. These critical situations appeared at varying times within a block. Participants were instructed to perform a full stop brake when they perceived a red light or a stop sign. This resulted in a total of 54 full stop brakings, 18 for each task (visuomotor secondary task, auditory secondary task, driving task only).

2.4. Visuomotor secondary task

During the visuomotor task (Visual Task v2.20, developed by Daimler AG, 2008) a 3 × 3-matrix with 9 Landolt rings was presented on a separate 18-inch LCD-TFT display. The display was located at the central console where it replaced the navigation system. The 3 × 3 matrix contained eight identical rings and one distractor with the gap at a different position (Fig. 1). Participants had to determine the position of the distractor by pushing the matching button on an external number keypad (1–9) that was positioned at the actual position of the manual delivery of the lower central console. After pushing a button the next matrix appeared immediately. This secondary task

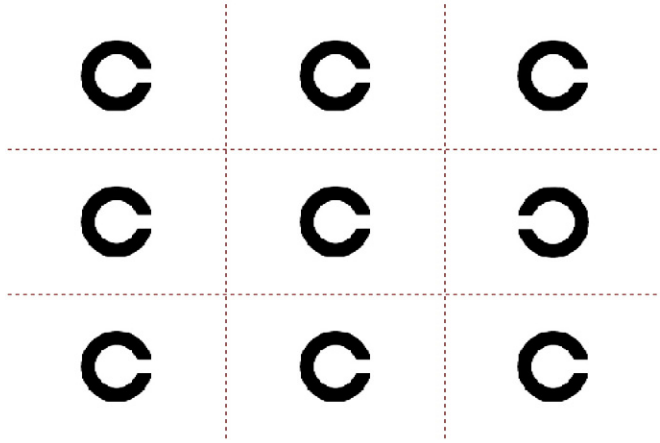

Fig. 1. Visuomotor task: 3 × 3-matrix.

lasted for three minutes. Participants were instructed to leave the right hand on the number keypad during this period. The number of correctly identified distractors served as the performance measure.

2.5. 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 detect the German definite article "die" [corresponding to "the" for female nouns] by pressing a button fitted to their left index finger and thumb. In every chapter the target word "die" appeared between 17 and 19 times. The number of detected target words served as the performance measure. At the end of each 3-minute block participants were instructed to answer a question about the content of the preceding section by choosing 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 audition.

2.6. Test procedure

Before starting the simulation, participants had to do a supervised baseline, where ocular artifacts (blinks, saccades) and muscle artifacts (head movements, chewing, brakes) were recorded, followed by a short practice, where they had to perform the visuomotor and the auditory secondary tasks for three minutes each without driving to get familiar with these tasks (Baseline 1). Afterwards participants received five minutes to get used to the primary driving task.

For the main study, participants had to drive one course twice, each consisting of 3 blocks (resulting in a total of six blocks). In every block they drove three minutes while performing the visuomotor secondary task, 1.5 min of driving with no additional secondary task, three minutes of driving while performing the auditory secondary task and again 1.5 min driving with no secondary task (see Fig. 2). The beginning and the end of every task was announced verbally. Data collected during these announcements were excluded from further analyses. The driving experiment was a continuous task so that the arousal level was not influenced by breaks between blocks with the exception of the transition between the third and the fourth block during which participants were offered a brief opportunity to drink some water. For the whole study participants had to drive a total of 18 min in each condition (auditory, visuomotor and driving only).

After the main study, participants again received five minutes to perform the primary driving task. Finally, the simulation was stopped and participants had to perform the visuomotor and the auditory secondary task for three minutes each without driving (Baseline 2).

2.7. Physiological recordings

After agreeing to the study participants were fitted with a 32-electrode-cap (ActiCap, Brain Products GmbH). A set of 24 electrodes were positioned according to the international 10–20 system. Four electrodes measured muscle activity around the musculus auricularis superior (T7, T8) and the sterno-cleido-mastoideus (TP9, TP10). Four facial electrodes measured horizontal and vertical eye movements. These were positioned about 2 cm above and below the right eye and at the left and right outer canthi (Fig. 3).

EEG was recorded relative to Cz and all impedances were maintained less than 10 kΩ. Data were digitized at 250 Hz with a band pass-filter (low: 0.531 Hz, high: 100 Hz) and a 50 Hz notch filter was applied to remove power line interference.

2.8. Pre-processing

Before correcting data from ocular and muscle artifacts, three references were compared for the parts of the supervised artifact baseline. Reference relative to Cz (standard for Brain Products Hardware), reference to linked Mastoid and common average reference (23 EEG electrodes, Fp1 was excluded). In the literature different references are used for different tasks and there is no agreement for one standard reference used for all cases (Nunez, 1981). In this study recordings should be robust to muscle activity or eye movements, hence the influence of artifacts during the controlled artifact baseline on the EEG activity should be minimized. The impact of artifacts was least for common average reference compared to linked Mastoid (high influence of musculus auricularis superior and sterno-cleido-mastoideus) and Cz (influence of muscle and marginal

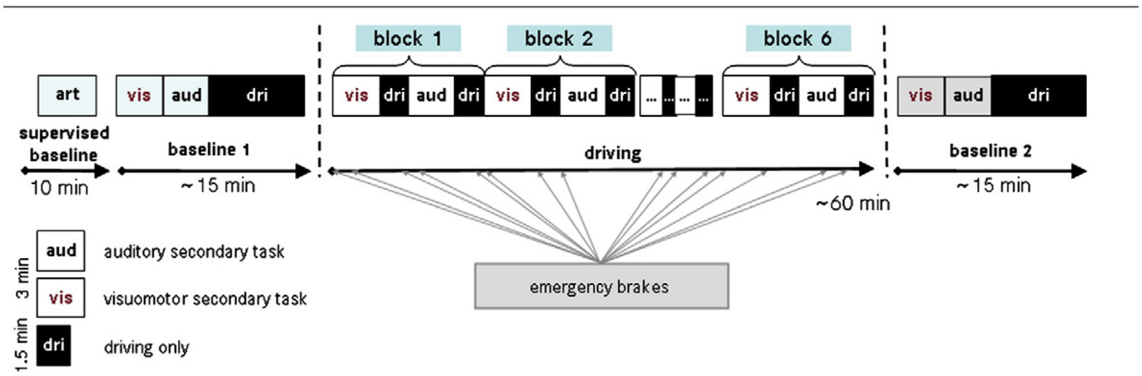

Fig. 2. Test procedure.

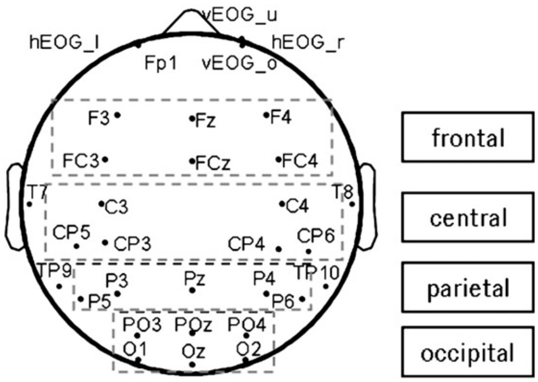

Fig. 3. Regions of interest (a total of 32 electrodes): to investigate the distribution of alpha spindles, the 23 EEG channels were divided into four regions.

ocular activity). Therefore, data was re-referenced offline to common average.

EEG-data (23 channels) were corrected off-line, eye-blink artifacts were removed using Independent Component Analysis (ICA, algorithm: acsobiro), available in the EEGLab toolbox (Delorme and Makeig, 2004). ICA was computed over the whole data set including both baseline and main study. Components that represented horizontal and vertical eye movements were selected by searching for characteristic patterns (temporal and spatial) in the segments of supervised artifact baseline. These components were excluded from further analysis.

Simon et al. (2011) reported a method based on time-frequency decomposition to automatically detect alpha spindles. In this method, the signal of an EEG channel is divided into segments of 1 s duration and 750 ms overlap. After subtracting the segment mean, each segment is multiplied by a Hamming window. The segment duration is chosen in order to contain at least four complete cycles of the lowest alpha oscillation of 6 Hz within one segment, where the attenuation at the boundaries due to windowing is taken into account. After segment-wise FFT computation, it is checked whether the spectral maximum between 3 to 40 Hz lies within the alpha band. In order to distinguish the alpha peak from non-rhythmic EEG background activity and other noise sources, an exponential curve is fitted to the mean amplitude spectrum (mean of all single segment spectra), which models the typical 1/f-like EEG spectrum (Pereda et al., 1998). This curve is adapted to the current noise power, by scaling it with ratio of the current segment power to the mean signal power of all segments. If the area under the peak (bounded by the half maximum amplitude) is at least twice as large as the area below the exponential curve in the same frequency range, the segment is classified as containing an alpha spindle. Successive segments with spindle activity are grouped together into one spindle. Each spindle with its typical "waxing and waning" (Shaw, 2003) can be characterized by its spectral peak amplitude, frequency and duration, computed as the average over all consecutive segments belonging to one spindle. Further, in a moving average window of one to several minutes, the occurrence rate of spindles (alpha spindle rate) can be computed. The extracted parameters are less noise susceptible and adapt to the particular alpha characteristics of the subject, both in time and frequency domain.

For the band power, each EEG channel was divided into segments of 20 s length, centred and multiplied with a Hamming window. After computing FFT for each segment, band power was applied for a widened alpha (6–13 Hz) and lower gamma (31–49 Hz) band.

In order to minimize artifacts that could not be handled by the ICA algorithms, an artifact 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 artifacts were excluded from further analysis. Alpha spindles that were detected within an artifact were not counted and the exact time period in which an artifact occurred was excluded when computing the alpha spindle rate per minute. 17.8% of all detected spindles were excluded from further analysis. For the calculation of band power, the complete artifact was excluded from the analysis (20.7% of data).

Statistical analysis was performed using MATLAB (R2009b) and PASW Statistics 18.

2.9. Experimental design

There were three independent variables, *time-on-task* (six blocks), *distraction* (visuomotor secondary task, auditory secondary task, driving only) and *channel group* (frontal, central, parietal, occipital). The dependent variables were EEG measures of attention (i.e., *alpha spindle rate, alpha spindle duration, alpha- and gamma band power*), performance measures from the primary task (brake reaction times on traffic lights and stop signs) and performance measures from the secondary tasks (correctly identified Landolt ring distractors and words in the visuomotor and auditory secondary task, respectively).

An a priori statistical power analysis using G*Power 3.1.2 (Faul et al., 2009) showed that in order to detect differences among the three levels of the variable distraction effects of $f = .40$, given a correlation among the levels of the repeated measures variable of $\rho = .5$, a nonsphericity correction of $\varepsilon = .6$, and $\alpha = \beta = .05$, a total sample size of 26 was needed. A post-hoc power analysis showed that given a final sample of $N = 28$, the power $(1 - \beta) = .97$ was slightly higher than required.

Analysis of variance (ANOVA) was used for all within-subject comparisons to identify the effect of *time-on-task* and *distraction* for each dependent measure. The level of α was set to .05 for all analysis. Whenever H_0 had to be rejected, the partial η^2 is reported as a measure of relative effect size. Statistically significant results for the variable distraction were subjected to post-hoc analyses using comparison of simple main effects with Sidak's alpha adjustment. For the variable time-on-task a post-hoc trend analysis was calculated using polynomial contrasts. Only significant differences and trends are reported.

3. Results

3.1. EEG

3.1.1. Distraction and time-on-task

Sphericity (Mauchly's Test of Sphericity) can only be assumed for the independent variable *distraction* with respect to the dependent variables *alpha spindle rate* and *lower gamma band frequency*. In all other cases Greenhouse–Geisser corrected values are reported.

In Table 1 the results of the ANOVAs are summarized for the effects of *time-on-task* and *distraction*. Reported values are means over all cortex areas (23 channels). The alpha spindle rate of the first (M = 10.31, SD = 1.73) and the second 1.5 minutes of driving only (M = 10.30, SD = 1.03) within one block were merged. Repeated measures *t*-test showed no significant differences for every six blocks.

A significant difference between *alpha spindle rate* (Fig. 4) and *alpha spindle duration* (Fig. 5) for the variable *time-on-task* could be found. Significant linear trends show an increase in *alpha spindle rate* and *alpha spindle duration* as a function of the time spent on the task. For the variable *distraction,* significant differences among the three distraction conditions could be found for *alpha spindle rate* and *alpha spindle duration*. Pairwise comparisons showed that *alpha spindle rate* is highest while performing the auditory secondary task followed by driving without secondary task and lowest for the visuomotor secondary task. *Alpha spindle duration* was significantly higher for driving with the visuomotor secondary task than for the auditory secondary task and driving only. No significant differences

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

Factor	Measure	Main effect			Trend analysis (polynomial)			
		$F(5,135)$	p	η^2	Type	F	p	η^2
Time-on-task	Spindle rate	24.371	<.001	.474	Linear	44.631	<.001	.623
	Spindle duration	10.717	<.001	.284	Linear	18.074	<.001	.401
	Alpha band power	.255	ns.					
	Gamma band power	1.383	ns.					
		Main effect			Pairwise comparison (sidak)			
		$F(2,54)$	p	η^2	Post-hoc effect			p
Distraction	Spindle rate	37.130	<.001	.579	Auditory > visuomotor			<.001
					Auditory > driving			<.001
					Driving > visuomotor			<.001
	Spindle duration	13.432	<.001	.332	Auditory > visuomotor			.003
					Driving > visuomotor			.001
	Alpha band power	5.235	.024	.162	Auditory > driving			.050
	Gamma band power	7.125	.002	.209	Driving > auditory			.003

could be found for the *alpha spindle duration* between driving with the auditory secondary task and driving only. The frequency of the occurred spindles within the widened alpha band was between 6.8 and 11.2 Hz with high fluctuations between subjects (M = 9.03, SD = 1.01).

Additionally, the band power of the widened *alpha*- and the *lower gamma band* was investigated for the variables *time-on-task* and *distraction*. There were significant differences for the *alpha band power* and the *lower gamma band power* among the three distraction conditions. *Alpha band power* (Fig. 6) was significantly higher during driving with the auditory secondary task than during driving only. *Band power of lower gamma* (Fig. 7) was significantly higher during driving only as compared to driving with the auditory secondary task. There is no significant difference between the visuomotor secondary task and the auditory secondary task (p = .089).

3.1.2. Distribution of alpha spindles depending on the chosen reference

To investigate regional differences of the appearance of alpha spindles, the occurrence rate over four cortex regions (Fig. 3) was compared for three different references. Therefore, an additional ANOVA was computed. As shown in Table 2, there is a significant difference for the variable channel group for all three references. For common average reference, the activity of alpha spindles was most prominent for the central region, whereas less alpha spindles were detected over the parietal, frontal and occipital region. A similar distribution was found for reference to Cz where the peak activity also occurred over the central electrodes as compared to the remaining regions. For reference to linked Mastoid detected spindles were most prominent over the parietal, frontal and occipital region with the significantly lowest occurrence over the frontal lobe, see also Fig. 8.

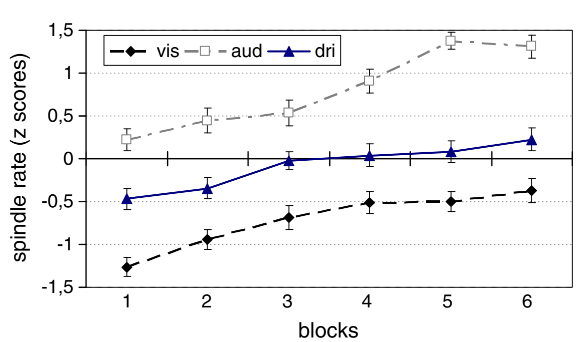

Fig. 4. Alpha spindle rate (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

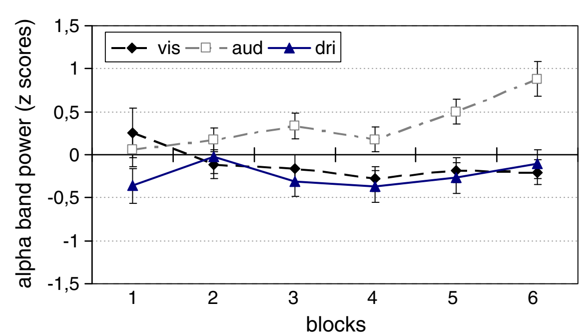

Fig. 6. Alpha band power (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

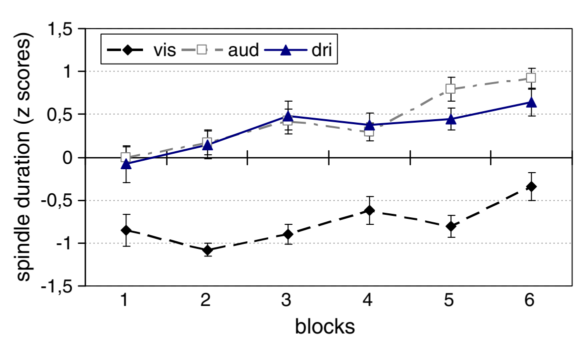

Fig. 5. Alpha spindle duration (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

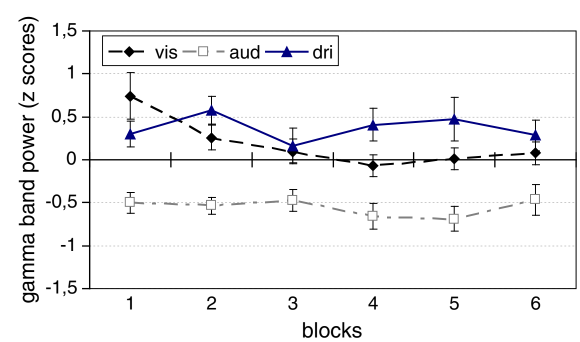

Fig. 7. *Gamma band power* (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

Table 2
Statistical results (ANOVA for repeated measures), alpha spindle rate for the variable *channel group* with different references before ICA artifact removal (com av = common average, mastoid = linked Mastoid, cz = reference to Cz).

Factor	Measure	Reference	Main effect		
			F(3,81)	p	η²
Channel group	Spindle rate	Com av	8.828	<.001	.246
		Mastoid	14.363	<.001	.347
		cz	7.013	<.001	.206
			Pairwise comparison (sidak)		
			Post-hoc effect	p	
Channel group	Spindle rate	Com av	Central > occipital	.017	
			Central > parietal	.011	
			Central > frontal	<.001	
	Spindle rate	Mastoid	Occipital > frontal	.003	
			Parietal > frontal	.001	
			Central > frontal	<.001	
	Spindle rate	CZ	Central > occipital	.042	
			Central > frontal	.002	
			Central > parietal	.057	

No significant interaction was found for the variables *distraction* and *channel group*. Additionally, ANOVAs for all four cortex regions show the same main effect (Table 3). The same effect of distraction on alpha spindles could be seen in each cortex region. There were significant differences among the levels of the variable *distraction* for the alpha spindle rate over all four investigated regions. The effect size was more pronounced in the parietal region ($\eta^2 = .575$). The trend analysis and the pairwise comparison show the same results as reported in Table 1.

3.2. Primary task

For reaction times of the full stop brakes (primary task) there were significant differences for both the variables *stimulus* ("traffic light", "stop sign") and *distraction* (see Table 4). Participants reacted significantly more slowly to the traffic light (M = 1238 ms, SD = 72 ms) than to the stop sign (M = 825 ms, SD = 19 ms). For the variable *distraction* we found faster reaction times for driving only as compared to driving with the auditory secondary task.

Table 3
Statistical results (ANOVA for repeated measures), alpha spindle rate for the variable *distraction* over different cortex regions (common average reference).

Factor	Measure	Region	Main effect		
			F(2,54)	p	η²
Distraction	Spindle rate	Occipital	30.624	<.001	.531
		Parietal	36.493	<.001	.575
		Central	30.426	<.001	.530
		Frontal	22.896	<.001	.459

There was also a significant interaction between the variables *distraction* and *stimulus*. Participants reacted more slowly to traffic lights during driving only compared to driving with the auditory secondary task ($p = .001$) or during driving with the visuomotor secondary task ($p = .022$) , while we found no significant differences for reaction times on stop signs. For reaction times we found no significant differences for *time-on-task*.

3.3. Secondary tasks

To investigate the effect of learning to perform the visuomotor task, the performance in Baseline 1 (before the main study) was compared with Baseline 2 (after the main study, see Fig. 2). Only 25 datasets were analyzed because three participants did not complete the second baseline due to technical defects. A two-sided *t*-test for paired samples showed a significant effect ($t(1,25) = -5.513$, $p < .001$). Participants had a higher score in Baseline 2 (M = 90.2, SD = 16.1), as compared to Baseline 1 (M = 74.6, SD = 11.1). Also, for the visuomotor task during driving there was a significant effect for *time-on-task* (ANOVA for repeated measures: $F(5,135) = 17.935$, $p < .001$, $\eta^2 = .399$). The trend analysis showed a linear trend ($p < .001$, $\eta^2 = .553$). Performance in the final block (M = 57.1, SD = 18.2) was significantly higher than in the first of six blocks (M = 41.8, SD = 13.7). Generally, the performance was significantly higher (pairwise comparison; $p < .001$) in both baseline 1 and 2 as compared to the performance during driving in each of the six blocks.

For the auditory task, we found no significant difference between Baseline 1 (79% correct identified words) and Baseline 2 (78%). In the main study participants found 76% of all predetermined words ("die") in the text, and they could answer 80% of all questions correctly. We could not find effects of *time-on-task* for the auditory task.

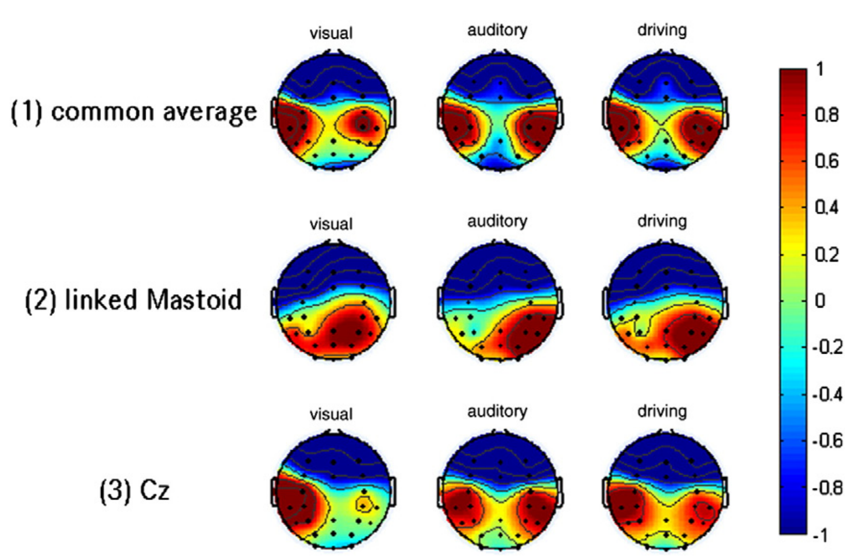

Fig. 8. Distribution of alpha spindles with regards to different references, calculated for each condition separately (values are z-scores of collectively occurred alpha spindles averaged over all participants).

Table 4
Statistical results (ANOVA for repeated measures), reaction times (primary task) for the variables *distraction* and *stimulus* (rt = reaction time).

Factor	Measure	Main effect			Pairwise comparison (sidak)	
		F(1,27)	p	η^2	Post-hoc effect	p
Stimulus	Reaction time	41.598	<.001	.606	Traffic light > stop sign	<.001
		F(2,54)	p	η^2	Post-hoc effect	p
Distraction	Reaction time	5.713	.015	.175	Auditory > driving	.003
		F(2,54)	p	η^2	post-hoc effect	p
Distraction × stimulus	Reaction time	41.598	.004	.224		
Distraction	rt: stop sign	2.226	ns.			
	rt: traffic light	6.770	.008	.200	Auditory > driving	.001
					Visuomotor > driving	.022

4. Discussion

4.1. Spindle parameters

For the two calculated alpha spindle parameters (rate, duration) the results suggest that alpha spindle rate is most reliable and sensitive to both kinds of driver distraction.

In line with our hypothesis there was a significant difference among the three investigated conditions (driving with auditory secondary task > driving only > driving with visuomotor secondary task), whereas the *alpha spindle duration* is lower for the visuomotor secondary task as compared to the auditory secondary task and to driving only. The increase in spindle rate especially during the auditory secondary task arises from a continuous active inhibition of visual information processing. A similar response of alpha activity occurs during internalized attention (Cooper et al., 2003). Dividing attention between the mainly visual primary task and the auditory secondary task leads to a shift of attention away from the visual modality. Foxe et al. (1998) followed a different approach by intentionally inducing these attention shifts by cueing attention to either modality before presenting an audio-visual stimulus. Active focusing on the auditory stimulus in preparation for the anticipated auditory input also led to increased ~10 Hz amplitude. The authors proposed an active inhibition of the visual attentional system for the benefit of the attentionally more relevant auditory input. This process of shifting attention away from visual to auditory input is also expected to be the reason for increased occurrence of alpha spindles.

For investigating the appearance of these spindles, the differences of the alpha spindle rate among the three different distraction conditions between four different cortical areas (frontal, central, parietal, occipital areas; Fig. 3) were analyzed. Parameter values for channels within one region were averaged. Previous findings reported of alpha activity being most prominent over parietal regions (Schmidt et al., 2009) or parietal and occipital regions (Schmidt et al., 2000). For the tasks used in this study, the task-related changes in alpha spindle activity could be observed in all four cortex regions. Even though there was a significantly higher alpha spindle rate over the central region as compared to the frontal region, we found that these absolute level distinctions depend on the chosen reference. When calculating the spindle rate for data referenced to Cz and linked Mastoid, the relative differences for the main effects remain equal, but the absolute number of detected spindles in different cortex regions changes. Calculating z-scores relative to the rest of the head shows similar distributions for each condition independent of the absolute number of alpha spindles (Fig. 8). Irrespective of the chosen reference, we observed a broad distribution of effects on alpha spindles over the cortex.

Alpha spindles in the awake state are assumed to be controlled by interplay between thalamic relay cells and the thalamic reticular nucleus, as well as cortical regions (Pfurtscheller, 2003). This allows the thalamus to provide a dynamic relay that affects the nature and format of information that reaches the cortex (Pfurtscheller and Lopes da Silva, 1999; Sherman, 2001). We suggest that the reported effects on the *alpha spindle rate* (lower occurrence) and the *alpha spindle duration* (shorter spindles) while performing a visuomotor secondary task on top of the driving task are due to a more frequent change of viewing direction as well as higher attentional demands and therefore indicate a higher and more variable visual input load.

4.2. Time-on-task

Time-on-task also had a strong effect on the *alpha spindle rate*, suggesting that this parameter is also a valid indicator of driver fatigue. Even though the participants were driving in the simulator for only about 1.5 hours, most people reported that they got tired during driving. This is a well-known phenomenon for simulator studies, where effects of fatigue are more prominent compared to real driving (Philip et al., 2005). Of all measures analyzed in this study, the alpha spindle rate most strongly reflects this time-on-task related change of driver fatigue.

The present findings nicely fit those of Simon et al. (2011) who reported that fatigue was most strongly reflected in the *alpha spindle rate* during real daytime driving, when they compared the first and the last 20 min of driving from participants who aborted driving on the road at an early stage due to severe fatigue. In this study a strong increase of the alpha spindle rate could be observed with time-on-task which can be explained with a decreased processing of visual stimuli due to increasing fatigue.

4.3. Alpha band power

Foxe et al. (1998) could further show that alpha power is related to the modality attended to (visual or auditory). The significant main effect of distraction on alpha spindle rate and alpha band power is in agreement with these results. Various conditions resulted in different levels of alpha spindle generation. Regarding alpha band power this discrimination was not possible. While both measures can distinguish modality specific attention, the alpha spindle rate also discerns different levels of attentional demands within one modality. The greater sensitivity of the alpha spindle measure within this context can be attributed to its higher robustness against artifacts and the extraction of subject-specific alpha band activity. This fits with the results of Simon et al. (2011), who also found that the alpha spindle rate was a more sensitive indicator of driver fatigue than the alpha band power. These findings suggest that, as compared to the alpha band power computed with the Welch periodogram, the alpha spindle rate is a more sensitive measure to determine driver states and is more robust to artifacts, which is inevitable in highly ecologically valid settings like car driving.

4.4. Gamma band power

Regarding the literature on attention, gamma band power has been found to be a good indicator of selective attention (Fell et al., 2003; Landau et al., 2007; Jensen et al., 2007). However, these results were found under laboratory conditions, in which a well-controlled amount of stimuli is presented to relatively immobilized participants. Even under simulated driving conditions, the variety of impulses that stimulate the human's brain is difficult to control, and gamma activity is contaminated by a fair amount of muscular artifacts.

For instance, we found high EMG activity between 30 and 100 Hz over the temporal lobe (electrodes T7, T8, TP9 and TP10) during all test conditions which is evidence for high muscle activity while driving in the simulator. Lutzenberger et al. (1997) suggested only interpreting differences in EEG-data when EMG does not show a similar difference.

There were significant differences for *gamma band power* over the temporal lobe for driving with the auditory secondary task as compared to driving with the visuomotor secondary task (pairwise comparison: $p<.001$) and driving only ($p<.001$). Hence, the results reported above can be explained by lower muscle activity and a calmer driver behavior during listening to an audio book. Therefore we think that it is not possible to reliably measure brain activity in the gamma band in real-road or even simulated driving situations.

4.5. Primary and secondary tasks

The primary task was a low demanding simulated driving task in which participants followed a mostly straight road where they had to react to traffic lights and suddenly appearing stop signs. It seems possible that the driving task, especially the braking to stop signs, was very easy so that no significant differences could be found in reaction times between driving with or without additional distraction. In contrast, braking to less salient traffic lights was apparently more difficult which required a higher concentration on the driving scene, so that the distracting tasks led to a significant effect on reaction times.

The decreased performance in the secondary tasks during the driving task as compared to the baseline shows that participants had to divide their attention to both the driving task and the secondary tasks.

4.6. Future research

In this study effects of visuomotor and auditory secondary tasks on the driver's cortical activity in a driving simulator were investigated. *Alpha spindle rate* and *alpha spindle duration* seem to be promising parameters that can be robust enough to be applied in less regulated situations. Future studies should aim to transfer this design to a real road driving study.

Additionally, it will be necessary to connect the found parameters with driving performance in a real-road driving situation.

It also has to be investigated if there is less visual input and therefore longer reaction times when more alpha spindles are detected. We assume that there is a link between the occurrence of alpha spindles and the "looking but failing to see"-phenomenon (Staughton and Storie, 1977).

Probably there are different neurophysiological elicitors or different consequences in behavior for alpha spindles during a secondary task compared with alpha spindles in ongoing fatigue. The relationship between these two different processes should be subject to further investigations.

5. Conclusion

We conclude that there is additional information aside from the occurrence of alpha spindles due to already shown long-term effects caused by fatigue. Short-term variations of the alpha spindle rate can be interpreted as an active inhibition of driver's visual perception. A higher spindle rate represents decreased visual information processing, associated with a shifting of attention away from the primary driving task either due to fatigue or because attention is attracted by a task in a different modality, i.e. to the auditory secondary task in the present case. The results are consistent with the assumption that alpha spindles indicate active inhibition of visual information processing. Effects on the alpha spindles while performing secondary tasks on top of the driving task indicate attentional shift according to the task modality.

When compared with traditional *alpha band power*, *alpha spindle rate* and *alpha spindle duration* were more sensitive to the experimental manipulations. In the next step we will aim to replicate these results in a real road driving study, an even more dynamic and uncontrolled setting with probably more noise and artifacts.

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