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Drivers' misjudgement of vigilance state during prolonged monotonous daytime driving

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ABSTRACT

To investigate the effects of monotonous daytime driving on vigilance state and particularly the ability to judge this state, a real road driving study was conducted. To objectively assess vigilance state, performance (auditory reaction time) and physiological measures (EEG: alpha spindle rate, P3 amplitude; ECG: heart rate) were recorded continuously. Drivers judged sleepiness, attention to the driving task and monotony retrospectively every 20 min. Results showed that prolonged daytime driving under monotonous conditions leads to a continuous reduction in vigilance. Towards the end of the drive, drivers reported a subjectively improved vigilance state, which was contrary to the continued decrease in vigilance as indicated by all performance and physiological measures. These findings indicate a lack of self-assessment abilities after approximately 3 h of continuous monotonous daytime driving.

1. Introduction

Following Mackworth (1957), who defined vigilance as "the state of readiness to detect and respond to certain specified small changes occurring at random time intervals in the environment," driving can be classified as a vigilance task, especially when it is performed in a monotonous environment with little task demand. This also follows Parasuraman's (1998) somewhat broader definition of vigilance as "the ability to sustain attention to a task for a period of time". Fluctuations in vigilance in general and a vigilance decrement in particular constitute a serious risk to traffic safety.

As approximately 15–20% of the fatal accidents can be ascribed to sleepiness and fatigue (Hell and Langwieder, 2001; CARE, EU road accidents database, 2009), Europe was faced with at least 6000 vigilance-related fatalities in 2007, the most common and severe cause of these accidents being the driver falling asleep while driving. Typically carried out in driving simulators, at night and oftentimes with sleep-deprived participants, a fair amount of driving studies investigated the occurrence of microsleeps (Boyle et al., 2008; Moller et al., 2006; Papadelis et al., 2007). However, there is evidence from accident data (Folkard, 1997) as well as from experimental studies (Thiffault and Bergeron, 2003) that vigilance fluctuations have a significant negative impact on driving safety also during daytime driving and especially under monotonous conditions (Dinges, 1995). Unfortunately, there are only few daytime driving studies investigating drivers' vigilance states under monotonous conditions, and only a subset of those studies were conducted in a real road situation (Brookhuis and De Waard, 1993; Tejero and Choliz, 2002). Based on the finding that fatigue develops differently in a simulator as compared to real road driving conditions (Belz et al., 2004; Philip et al., 2005) we decided to conduct a road driving study in real traffic in order to maximize the ecological validity of the results. Given the debate on how well people are able to judge their own vigilance state (see Section 1.2) it seemed appropriate to put a distinct focus on a possible dissociation between the drivers' self-assessment on one side and performance as well as physiological indicators of vigilance on the other.

1.1. Factors affecting vigilance in driving

Thiffault and Bergeron (2003) pointed out that factors affecting vigilance can be divided into exogenous and endogenous factors

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depending on whether they stem from within the organism or whether they are caused by characteristics of the task performed. Vigilance can be influenced by monotony which may itself serve as a cause or a multiplier of fatigue or sleepiness (Dinges, 1995; Thiffault and Bergeron, 2003). Monotony of the road environment is therefore classified as an exogenous factor. It constitutes the central factor imposed in our experimental design. In terms of Wertheim's (1991) definition, monotony in driving is not only caused by a lack of alerting stimulation but also by a high predictability of the situation.

Fatigue is exogenously influenced as it follows sustained activity and can be overcome by rest (Philip et al., 2005). Desmond and Hancock (2001) further differentiated between active fatigue following a task that requires continuous and prolonged perceptual-motor adjustments and passive fatigue which develops in a monitoring task with only rare perceptual-motor response requirements. As the task of monotonous driving integrates both sorts of fatigue we prefer the term task-related fatigue here.

Sleepiness can be defined as the difficulty in remaining awake (Philip et al., 2005). It is influenced by circadian and homeostatic variables. It is thus endogenously based and can be reduced after sleep. In our experiment we did not directly manipulate participants' sleepiness (e.g., by sleep deprivation) but focused on introducing a vigilance decrement by task characteristics.

Independent of whether monotony, fatigue or sleepiness (or any combination thereof) reduces drivers' vigilance, the best method to improve a reduced vigilance state is to stop the car and take a break, ideally including a short nap (Horne and Reyner, 1999). Therefore, the drivers' ability to correctly judge their vigilance state is of great importance for traffic safety.

1.2. Self-assessment of vigilance

Research on the reliability of the self-assessment of vigilance state has led to contradicting results. Several studies showed that self-ratings are not sufficiently accurate to serve as reliable and valid indicators of reaction times, driving performance or sleep propensity (Belz et al., 2004; Lenné et al., 1997; Moller et al., 2006; Philip et al., 1997, 2005). For instance, Philip et al. (2003) reported that self-assessment of subsequent performance in a reaction time task was rather poor under prolonged daytime driving conditions.

Data obtained in other studies, most of which were conducted under conditions of sleep deprivation or at night-time, suggested that people are generally capable of judging possible performance impairments in tasks such as in driving (Baranski, 2007; Horne and Baulk, 2004; Lisper et al., 1986; Nordbakke and Sagberg, 2007). Therefore one could argue that people are well aware of their deteriorating vigilance, but that early warning signs are often ignored or misinterpreted. Another explanation for these disputed results might have been the use of different vigilance measures across the different studies. In order to gain a more complete picture of the drivers' self-assessment ability, we decided to study a set of objective and subjective measures in a single study.

1.3. Objective measures and their use in studies on monotonous driving

1.3.1. Performance measures

Given that a reduction in vigilance is actually defined by a performance decrement (Mackworth, 1957), performance measures have high face validity for the evaluation of vigilance states. From a safety perspective we had to avoid a state where ongoing driving performance would be too seriously degraded. Nevertheless it was our objective to detect even minor changes in vigilance state that might lead to a reduced ability to respond to unforeseen events. We therefore decided to implement a simple secondary auditory task that most likely would not interfere with the motor requirements of the driving task, assuming that even minor reductions in vigilance should first be reflected in secondary task performance. To ensure that the auditory task would be performed as a secondary task in accordance with the subsidiary task paradigm (O'Donnell and Eggemeier, 1986), participants were explicitly instructed to prioritize the primary task of driving. In addition, it was to be expected that the potentially high costs of errors would also cause participants to give the highest possible priority to the driving task.

In the context of a real driving situation, Laurell and Lisper (1978) demonstrated that a secondary task was sensitive to changes in vigilance and predictive of brake reaction time. Other studies showed that slow reactions (as opposed to fast ones) are particularly sensitive indicators of states of reduced vigilance (Graw et al., 2004; Williams et al., 1959).

1.3.2. Physiological measures

As the primary physiological method we used electroencephalography (EEG) to measure the driver's brain activity continuously. From the various measures that can be derived from the EEG we decided to use the spontaneous alpha spindle rate that is a feature derived from the alpha-band (6–13 Hz) which has been shown to correlate with changes in vigilance in the driving context (Kecklund and Akerstedt, 1993; Papadelis et al., 2007; Tietze and Hargutt, 2001). Based on these earlier findings we implemented an automated algorithm that extracts the alpha spindle rate from the continuous EEG. The main reasons for preferring this measure to the classic power measures are its robustness against external noise and artifacts as well as its superior specificity to changes in vigilance. We also assessed the amplitude of the stimulus-induced P3 event related potential (ERP, for a review see Polich, 2007) that has also been shown to be sensitive to changes in vigilance (Koelega et al., 1992). The P3 amplitude can be interpreted as a measure of the processing depth of the auditory stimulus. Additionally, the participant's heart rate was recorded as an indicator of the physical activation level which has also shown to be sensitive to vigilance changes (O'Hanlon and Kelly, 1977). For a thorough review of objective driver state measures we refer to Tejero Gimeno et al. (2006).

1.4. Hypothesis

We hypothesized that all objective measures would indicate a monotonous reduction in vigilance state as a function of the distance driven (i.e. an increase of the mean of the slow reaction times; an increase of the alpha spindle rate; a decrease of the P3 amplitude and heart rate). Following the controversy concerning the drivers' self-assessment ability we refrained from formulating a specific hypothesis about the effect of driving distance on subjective measures of vigilance.

2. Methods

2.1. Participants

Twenty-nine right-handed participants (20 males, 9 females; age: $M = 29.2$; range: 23–49) with extensive driving experience (mean driving distance of approximately 20,500 km, i.e. 12,000 miles per year) were recruited on a voluntary basis for an "in-car EEG-study on attentional processes". Participants were screened for a variety of exclusion criteria (handedness, auditory and visual disabilities, and various illnesses), instructed to sleep regularly the night before the experiment, and to refrain from consuming caffeine in the morning on the day of the experiment. For their participation they received compensation in form of a gift worth approximately € 25.

The size of the sample available for data analysis was reduced due to technical problems leading to insufficient EEG data quality

Table 1
Subjective measures.

Concerning the time period since the last prompting. . .									
KSS	. . .how would you describe your predominant state?								
	Extremely alert		Alert		Neither alert nor sleepy		Sleepy, but no difficulty remaining awake		Extremely sleepy, fighting sleep
	1	2	3	4	5	6	7	8	9
ATT	. . .how attentively have you been driving?								
	Extremely attentively		Attentively		Neither attentively nor inattentively		Inattentively		Extremely inattentively
	1	2	3	4	5	6	7	8	9
MON	. . .how did you perceive the drive?								
	Extremely varied		Varied		Neither varied nor monotonous		Monotonous		Extremely monotonous
	1	2	3	4	5	6	7	8	9

(six participants), lack of compliance (two participants) and fatigue-related break-offs (three participants). As a result, 19 (14 males, 5 females; age: M = 29.4, range: 23–49) complete data sets containing all measures were available for statistical analysis.

2.2. Materials and procedures

On the test day the participants arrived at the lab at 10:30 am and signed an informed consent form. While the physiological recording equipment was applied, the participants completed German versions of the morningness–eveningness–questionnaire (D-MEQ; Griefahn et al., 2001) and the Edinburgh handedness inventory (Oldfield, 1971). To control for possible circadian (Folkard, 1997; Lenné et al., 1997) and nutritional effects (Smith and Miles, 1986) all participants had lunch at 11:30 am before a 30-min EEG-baseline containing typical body movements and resting-EEG was recorded in the car. The baseline was recorded in order to allow for research on advanced EEG-artifact processing; these data are not presented here.

Following the German legal maximum driving duration for commercial drivers (4.5 h) the length of the drive was set to approximately 4 h, resulting in an experimental course of 428 km (about 267 miles) on the A 81 Autobahn (between exits Ehningen and Gottmadingen). This route was subdivided into four sections of 107 km length, each section thus corresponding to about an hour of driving time. In an attempt to ensure as much monotony as possible, the participants drove on this low-traffic highway off rush hour times. For practical reasons we started and ended the experiment close to an urban area, which implies that the initial and final sections comprised several kilometres on an interurban Autobahn. According to statistics of the German Federal Highway Research Institute (Fitschen et al., 2007) this resulted in a significantly higher average traffic density for sections 1 and 4 as compared to sections 2 and 3 (Fig. 1).

Participants started the drive at 12:45 pm and returned, on average, after about 3:45 h of driving, except for cases in which the experiment was terminated early by the participants. Three predefined turns were necessary and interrupted the continuous run at about 1:00, 1:40, and 2:20 h cumulated driving duration.

Participants had to be sufficiently rested upon arrival. They knew that they could stop driving at any time without any monetary or other penalties. This occurred in three cases. For additional safety reasons, an investigator accompanied the participant in the car, continuously monitoring the driver and ready to intervene whenever necessary. The test car was a Mercedes-Benz S-Class (W221). The participants' task was to drive at a speed not exceeding 130 km/h (approximately 80 mph; recommended maximum speed on German highways) and to comply with the traffic rules at all times. They were instructed to use automatic shift and to refrain from turning on the radio or using other in-car devices. Further, participants were asked not to talk to the investigator and to avoid unnecessary movements in order to reduce artifacts in the EEG recording.

2.3. Subjective measures

As a compromise between a high temporal resolution and a low amount of intrusion we decided to prompt the drivers every 20 min for their retrospective vigilance assessment. As vigilance indicators we used a well-established single-item indicator of sleepiness (Karolinska Sleepiness Scale, KSS; Åkerstedt and Gillberg, 1990) and two similarly constructed items assessing inattention (ATT) and monotony (MON, for an overview see Table 1). The investigator verbally prompted the driver to judge sleepiness, inattention and monotony with regard to the previous 20 min of driving time.

2.4. Performance measures

The participants were instructed that the auditory oddball reaction time task was only to be completed if they felt that it was safe to do so in a given driving situation. The participants had to respond to infrequent target tones (500 Hz, 20% probability) that were presented in a random sequence mixed with frequent distractor tones (400 Hz, 80%) by pressing a button fitted to their right thumb. The inter-stimulus interval varied randomly between 4 s and 6 s. The

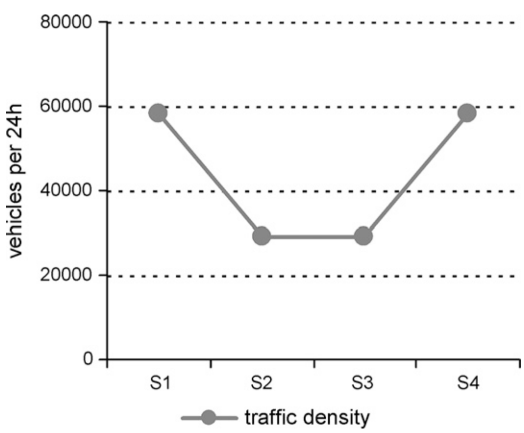

Fig. 1. Average 24 h traffic density.

constant pitch of the stimuli reduced their alerting potential to a minimum. Only button presses that fell into a response window of 200–4000 ms following stimulus presentation were analyzed. For every route section of 107 km, and separately for each participant, the mean of all reaction times above the 80%-percentile was calculated as a measure of the participants' slow reactions, and the mean of all reaction times below the 20%-percentile was calculated as a measure of participants' fast reactions. Consistent with Williams et al. (1959) we decided to focus on the mean of the slowest reactions as these are known to be particularly sensitive to changes in vigilance state.

2.5. Physiological measures

EEG and electrocardiogram (ECG) were recorded from 128 electrodes (1000 Hz sampling rate, low cut-off: 0.016 Hz; high cut-off: 250 Hz) using BrainAmp recording hardware (Brainproducts GmbH, Munich). The EEG signal was down-sampled to 250 Hz and band-pass filtered (0.5–50 Hz); artifactual channels were excluded from further analysis. In order to minimize ocular and muscular artifacts, independent component analysis (Jung et al., 2000) was applied. Only those components carrying a temporal and spatial pattern resembling that of neural sources were accepted.

We used an automated algorithm to extract sharp spectral peaks within the alpha band (6–13 Hz), which we call alpha spindles, and to determine amplitude, peak frequency and duration of these peaks. In this paper we focus on the alpha spindle rate, which is the occurrence rate of alpha spindles within each of the four sections of the drive. As the alpha rhythm is most prominent over parieto-occipital sites we analyzed the signal of electrode Pz. To account for inter-individual differences an alpha spindle index was derived by dividing each section by the reference value of the first section.

To extract the P3 amplitudes the pre-processed EEG signal of electrode CPz was averaged time locked to the presentation of the oddball stimulus. A baseline-correction (relative to −200 ms to 0 ms pre-stimulus time window) was applied. The P3 amplitude then was defined as the maximum value of the signal in a time window from 300 ms to 600 ms post-stimulus minus the minimum value in a time window from 0 ms to 300 ms post-stimulus.

R-peaks were identified from the ECG using an automated algorithm in Matlab and the average heart rate was calculated for every experimental block.

2.6. Data reduction

In order to assess the subjective, performance and physiological correlates of monotonous driving, data epochs which clearly lacked monotonous driving (i.e. communication between driver and investigator, turning points, workload-inducing driving situations, traffic jams and short stops) were discarded from the data analysis. For that purpose, all situations which were noticeably non-monotonous were logged by the investigator accompanying the participant. This resulted in an average loss of 11.9% of the data (SD = 2.9). For all measures the mean over each section of 107 km length was calculated.

2.7. Experimental design

The only independent variable in our experimental design was the distance driven (four sections of 107 km each). Dependent variables were (a) subjective measures of vigilance (sleepiness [KSS], inattention [ATT] and monotony [MON]), (b) performance measures (slow and fast reactions) and (c) physiological measures of vigilance (alpha spindle rate (ASR), P3 amplitude (P3A) and heart rate (HR)).

An a priori statistical power analysis using G*Power 3 (Faul et al., 2007) showed that in order to detect effects of $f = .50$ assuming a population correlation among the levels of the repeated measures variable of $\rho = .50$ (estimated from pilot data) and given $\alpha = \beta = .05$, $N = 13$ participants were needed. A sensitivity power analysis showed that given a final sample of $N = 19$, effects of size $f = .39$ could be detected under otherwise identical conditions. A multivariate approach (MANOVA) was used for all within-subject comparisons to identify the effect of the driving distance variable for each dependent measure. All multivariate test criteria correspond to the same (exact) F-statistic, which is reported. 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 were subjected to post hoc trend-analyses using polynomial contrasts. Only significant linear and quadratic trends are reported.

3. Results

It was confirmed that all participants were right-handers (all handedness-indices >0). The D-MEQ results showed that the large majority of participants (15) fell into the neutral chronotype group. Considering the small variability in chronotype and the small sample size, we refrained from entering chronotype as a further factor into the analysis.

The results of the MANOVAs testing the effect of the driving distance variable (sections 1–4) on the dependent variables are summarized in Table 2. Significant quadratic trends for KSS and ATT indicate a relatively better subjective state at the beginning and at the end of the drive compared to the two middle sections (Fig. 2). The same pattern of results was found for the measure MON although the main effect barely failed to reach significance (Fig. 2).

Table 2
Statistical results.

	Main effect			Trend analysis			
	$F(3,15)$	p	η^2	Type	$F(1,17)$	p	η^2
Subjective							
MON	3.23	.053	.392	Quadratic	9.19	.008	.351
KSS	8.49	.002	.629	Quadratic	9.99	.006	.370
ATT	4.47	.020	.472	Quadratic	10.06	.006	.372
Performance							
Fast reactions	1.74	n.s.					
Slow reactions	6.38	.005	.561	Linear	13.36	.002	.440
Physiology							
ASR	5.05	.013	.503	Linear	9.77	.006	.365
P3A	3.74	.035	.428	Linear	10.25	.005	.376
Heart rate	11.86	<.001	.703	Linear	17.83	.001	.512

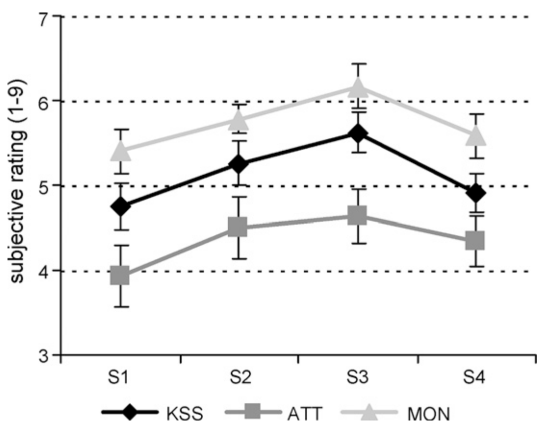

Fig. 2. Subjective measures (rating: 1–9). Error bars represent the standard errors of the means.

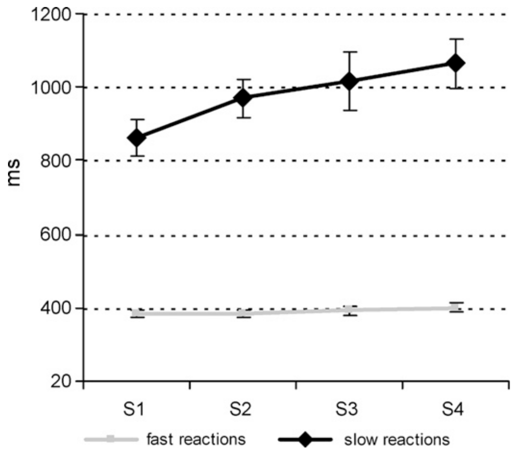

Fig. 3. Reaction times. Error bars represent the standard errors of the means.

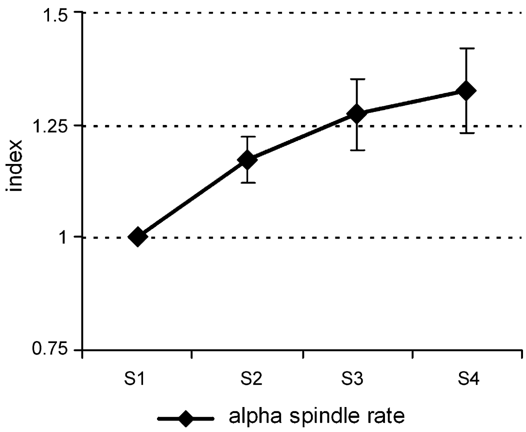

Fig. 4. Alpha spindle rate at electrode Pz (relative to first section). Error bars represent the standard errors of the means.

As expected, the mean of the fast reactions did not differ significantly among the four sections. In contrast, the mean of the slow reactions showed a significant effect in terms of a linear increase from section 1 to 4 (Fig. 3).

The same pattern of results was observed for the physiological measures (alpha spindle rate, P3 amplitude and heart rate, see Figs. 4–6). There was a linear increase in the alpha spindle rate and a linear decrease in the P3 amplitude and as well as the heart rate.

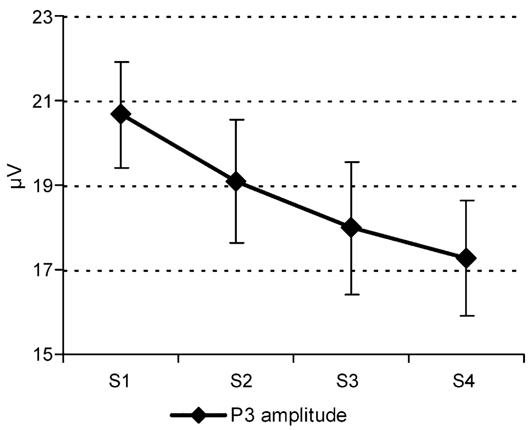

Fig. 5. P3 amplitude at electrode CPz. Error bars represent the standard errors of the means.

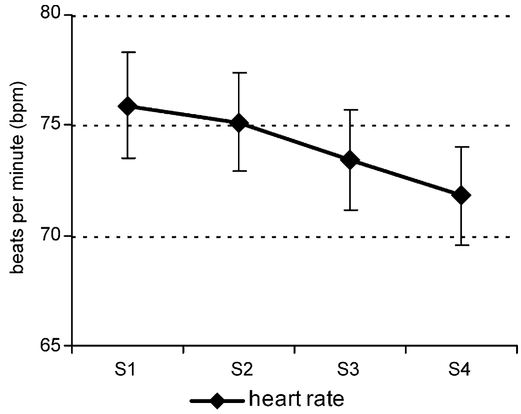

Fig. 6. Heart rate. Error bars represent the standard errors of the means.

4. Discussion

The participants' subjective evaluation of their vigilance level indicates that the induction of monotony was successful. It is also obvious that the quasi-experimental variation in traffic density led to a reduction of monotony at the beginning and at the end of the drive. Most interestingly, drivers reported a subjective improvement of their vigilance (as indicated by their assessments of their sleepiness and attention for the driving task) towards the end of the drive. However, this subjective improvement contradicted all objective measures of vigilance. Reaction times, EEG alpha spindle rate, P3 amplitude and heart rate consistently indicated a continuous reduction in vigilance even for the fourth and final section of the drive. This leads us to conclude that drivers in a reduced state of vigilance following prolonged and monotonous driving are vulnerable to a misjudgement of their objective vigilance state in terms of performance and physiological parameters.

4.1. Reason for misconception

It is not possible to clearly identify whether the subjective increase in vigilance in the final section of the drive was due to effects of circadian phase, increased traffic density, the (joyful) expectation that the drive would soon be over, or any combination of these variables. All these variables were confounded in the final section of the drive. This state of affairs does not reduce the practical relevance of the finding that self-assessment of vigilance may dissociate from objective measures of vigilance. Further research is needed to shed light on the interrelations of the variables that may cause this potentially fatal dissociation.

4.2. Reaction times

The increase in the slow reactions as compared to the fast reactions points to the validity of the separate analysis of the long reaction times. A possible problem is that the increase in traffic density in the fourth section of the drive may have resulted in a shift of attentional capacity away from the reaction time task towards the driving task. If so, then the observed increase in the long reaction times could be the result of an increased workload rather than a decrease in vigilance. However, this alternative explanation seems very unlikely, because a shift of attention towards the visual modality would have to be accompanied by a reduction in alpha spindle rate. This was clearly not the case. Conversely, if one wanted to interpret the EEG in light of an attentional shift, the observed increase in alpha spindle rate would imply a switch of attention towards the auditory task (Gladwin and de Jong, 2005). Further an increase in workload in the last section of the drive would have to be accompanied by an increase in heart rate. This was not observed either. Finally, given that the traffic density in sections 1 and 4 was nearly identical, reaction times also should have been nearly identical in these two sections if the speed of responding simply reflected traffic density related workload differences. Obviously, this was not the case.

While we cannot conclude with certainty from our data that the deterioration of reaction time performance in our auditory secondary task goes along with a reduced driving ability in terms of a reduced speed in responding to unforeseen events, it is possible to point to earlier research showing a positive correlation between auditory reaction times (Laurell and Lisper, 1978). In our case, travelling at a speed of 130 km/h the observed increase in slow reaction times of 200 ms in average corresponds to a potential increase in stopping distance of approximately 7 m. This significant increase underscores the safety relevance of our findings.

4.3. Future research

The present study was designed to investigate one driving course performed at a fixed time of day. Future studies should be aimed at uncovering how well the pattern of results observed here generalizes to other road environments and to different times of day and night. Future research is also needed to identify and evaluate potential countermeasures that, on one hand, decrease driver's proneness to the effects of monotonous driving and, on the other hand, support the driver's ability to judge his or her own state correctly. The present data show that this judgement ability is vulnerable under certain conditions. Research is thus needed on the acceptance of modern driver monitoring systems. Such systems might correctly judge the driver's state as inattentive while the driver feels alert enough to continue his drive. Educative actions communicating the shortcomings of human self-monitoring might be a promising approach here. Finally, performance and physiological measures might be suited to objectively identify particularly monotonous and therefore dangerous road environments that lead to an accelerated vigilance decrement, but this assumption, too, needs to be validated experimentally.

5. Conclusion

In conclusion, the data presented here show a good correspondence between subjective measures and reaction times as well as physiological measures for the first three of four sections of driving a long distance. All measures indicated a decrease in vigilance. However, in the fourth and final section of the drive a clear dissociation was observed between subjective and objective measures of vigilance. Given that all objective measures consistently point to a further decrease in vigilance in the fourth section, we must conclude that participants misjudged their subjective states at the end of the drive. Factors such as a less monotonous driving situation in the last section, the expectancy that the trip will be over soon or circadian phase might all have contributed to this misjudgement.

The present findings further support the potential benefit of driver assistance systems that constantly monitor the driver's state. This is especially true for systems that are sensitive to the early levels of inattentive driving. Given appropriate acceptance, these systems supply drivers with an objective evaluation of their ability to drive, they can keep drivers from continuing to drive following a misjudgement of their own state, and therefore they can reduce the probability of vigilance-related accidents.

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