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Event-related potentials and secondary task performance during simulated driving

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Abstract

Inattention and distraction account for a substantial number of traffic accidents. Therefore, we examined the impact of secondary task performance (an auditory oddball task) on a primary driving task (lane keeping). Twenty healthy participants performed two 20-min tests in the Divided Attention Steering Simulator (DASS). The visual secondary task of the DASS was replaced by an auditory oddball task to allow recording of brain activity. The driving task and the secondary (distracting) oddball task were presented in isolation and simultaneously, to assess their mutual interference. In addition to performance measures (lane keeping in the primary driving task and reaction speed in the secondary oddball task), brain activity, i.e. event-related potentials (ERPs), was recorded. Performance parameters on the driving test and the secondary oddball task did not differ between performance in isolation and simultaneous performance. However, when both tasks were performed simultaneously, reaction time variability increased in the secondary oddball task. Analysis of brain activity indicated that ERP amplitude (P3a amplitude) related to the secondary task, was significantly reduced when the task was performed simultaneously with the driving test. This study shows that when performing a simple secondary task during driving, performance of the driving task and this secondary task are both unaffected. However, analysis of brain activity shows reduced cortical processing of irrelevant, potentially distracting stimuli from the secondary task during driving.

Keywords: Simulated driving; Attention; Distraction; Secondary task; Event-related potentials

1. Introduction

Driving is a complex task in which several skills and abilities are involved simultaneously. Inattention during driving and distraction of the driver accounts for a substantial number of traffic accidents (Dingus et al., 2006; Klauer et al., 2006). The National Highway Traffic Safety Administration (NHTSA) and the Virginia Tech Transportation Institute (VTTI) reported that driver inattention is involved in 25–80% of traffic accidents (Dingus et al., 2006). Given the increased use of car electronics (e.g. phones, navigation systems), it is vital to understand the risk of using these potentially distracting technologies (AAA Foundation for Traffic Safety, 2001; NHTSA Driver distraction Expert working group meetings, 2000). Models of driving behaviour have been developed in which driving behaviour is explained with different levels of cognitive control (Ranney, 1994; Michon, 1985; Rasmussen, 1987). A distinction is made between skill-based behaviour (e.g. lane keeping, vehicle control), knowledge-based behaviour (e.g. planning the route), and rule-based behaviour (e.g. traffic manoeuvres). Whereas skill-based behaviour is largely automatic, rule-based behaviour requires controlled attention that is susceptible to distraction and interference from additional attention-demanding stimuli. Car electronics or conversations with another passenger bring about secondary task performance during driving and could therefore interfere with the rule-based behaviour required for driving a car (Horrey and Wickens, 2002; Michon, 1985; Brookhuis et al., 1991; Crundall et al., 2005; Strayer and Johnston, 2001).

Performing a secondary task during driving may interfere with the primary task, i.e. driving the car (Horrey and Wickens, 2002; Michon, 1985; Chaparro et al., 2005; Lamble et al., 1999; Levy et al., 2006). Furthermore, salient events that are irrelevant for driving may distract the driver from performing the driving task. However, the human information system has protective mechanisms against interference, especially against distraction by irrelevant events. According to Lavie (1995), the extent of

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processing task-irrelevant information is inversely related to the cognitive load imposed by the primary task. This leads to the prediction that during driving, the transition of a relatively low-load resting to a high-load active-driving situation should be accompanied by a reduction in processing irrelevant events (De Fockert et al., 2001; Lavie et al., 2003, 2004).

The impact of a secondary task on driving performance has been investigated in driving simulators and on-the-road. The secondary tasks used in these studies are mobile phone related tasks (e.g. having a phone-conversation or dialing numbers on a keypad), normal in-car conversations, and other secondary and auditory tasks (Brookhuis et al., 1991; Chaparro et al., 2005; Crundall et al., 2005; Lamble et al., 1999; Levy et al., 2006; Strayer and Johnston, 2001). The results of these studies show that the driving task deteriorates when a secondary task is performed simultaneously. This is consistent with the idea that a secondary task disrupts the driving task due to the diversion of attention from driving to the secondary task (Strayer and Johnston, 2001).

According to Wertheim's hypothesis on highway hypnosis, alertness is lower on highways and very familiar roads (Wertheim, 1978). Alertness can be assessed using the measurement of brain activity, i.e. the electroencephalogram (EEG; Lal and Craig, 2000, 2002; De Waard, 1996; De Waard and Brookhuis, 1991). Wertheim's hypothesis on highway hypnosis has been tested by means of recording EEG activity during driving (Cerezuela et al., 2004). These authors have shown that alertness was lower during driving on a highway than on conventional roads. Other studies also have reported a correlation between driving errors and low arousal as measured by EEG (Campagne et al., 2004).

EEG measurements only give an indication of the mental state of the driver. However, driving inattention can be the result of cognitive underload, leading to reduced arousal and inattention, or cognitive overload, leading to attention switching away from the primary driving task (De Waard and Brookhuis, 1991). One way to assess attention diversion from the primary driving task, is recording event-related potentials (ERPs) elicited by secondary, task-relevant or irrelevant stimuli, e.g. a secondary oddball task.

A classic oddball paradigm consists of standard stimuli and less frequent deviant target stimuli. In a three-stimulus oddball paradigm task-irrelevant novel stimuli are inserted into the sequence of standard and deviant target stimuli. An oddball task can be active, which means a person has to respond to the deviant target stimuli, or passive, which means no response is required. ERPs that are typically elicited in response to the oddball stimuli, are the Mismatch Negativity (MMN), the P3a, the P3b, and the reorienting negativity (RON). The MMN is elicited by a detection of any change in the stream of stimuli irrespective of the attention allocated to the stimuli (Gaeta et al., 2001; Näätänen et al., 1978, 2004; for a review, see Näätänen and Winkler, 1999). The MMN can be observed most clearly after the ERP elicited by the standard stimulus is subtracted from that elicited by the deviant stimulus during a passive oddball paradigm (Friedman et al., 2001). The P3a usually follows the MMN. The P3a is elicited by irrelevant novel stimuli and reflects the involuntary shifting of attention towards these stimuli (Hillyard et al., 1975; for a review, see Friedman et al., 2001). Following the P3a a late negativity can be observed called the reorienting negativity (RON). The RON reflects reorienting of attention towards task-relevant aspects of the primary task after attention has been involuntary switched to task-irrelevant aspects (Schröger and Wolff, 1998). The P3a can be distinguished from the P3b. The latter is elicited by relevant target stimuli in active task situations.

Several ERP studies support Lavie's theory (1995, 2003, 2004) with regard to decreased processing of task-irrelevant events when task-load increases. ERP amplitudes to secondary task stimuli have been found to be reduced during higher task-load conditions (Backs, 1997; Isreal et al., 1980; Singhal et al., 2002; for a review see Kok, 1997). However, attention allocation during driving, together with the effects of secondary task performance on driving performance, has not been thoroughly investigated. Therefore, the main purpose of the present study was to assess the impact of a secondary oddball task on driving performance. By recording ERPs in response to the secondary active and passive oddball task during driving, the extent of processing of the stimuli of the secondary oddball task was assessed. It was hypothesized that driving would be affected by performing a secondary task. Also it was expected that distraction by the irrelevant oddball stimuli would be reduced in both the active and passive oddball during driving relative to non-driving.

2. Methods

2.1. Subjects

Twenty healthy participants (2 males, 18 females), between 21 and 30 ($M = 23.1$, S.D. = 2.3) years of age, were recruited from the university population. They had normal or corrected-to-normal vision, normal hearing, were right handed, and reported being free of psychiatric or neurological disorders. Written informed consent was obtained prior to the study.

2.2. Steering simulator test

A modified version of the Divided Attention Steering Simulator (DASS) developed by Stowood Scientific Instruments (SSI, 2003) was used. The DASS has been used previously to investigate the effects of fatigue and sleep apnoea on driving performance (Juniper et al., 2000; Hack et al., 2000; Turkington et al., 2001, 2004; Philip et al., 2003). We only used one component of the DASS, the Steering Simulator (SS). The peripheral visual stimuli were removed from the DASS and an auditory oddball task was introduced instead, in order to enable ERP recording. In the DASS an image of a winding road with a vehicle on it is displayed on a computer screen. The vehicle is moving along the road and participants were instructed to keep the vehicle at the centre of the road using a steering wheel. No other traffic was involved in this test and the road did not contain traffic lights or crossings. Therefore, the lane-keeping task was not interfered by overtaking manoeuvres or other events. Primary outcome measure was the standard deviation of the car from the centre of the road (steering error).

1st 30-minute run	Oddball		Oddball		Oddball	Oddball
	5-minutes non-driving	20-minute drive				5-minutes non-driving
5-minute break						
2nd 30-minute run	Oddball	Oddball		Oddball		Oddball
	5-minutes non-driving	20-minute drive				5-minutes non-driving

Fig. 1. Schematic overview of task procedures.

2.3. Oddball task

The novelty-oddball paradigm consisted of eight 5-min blocks. Each 5-min block consisted of 130 stimuli, which were a pseudo-randomisation of 104 standard tones (80%), 13 deviant target tones (10%), and 13 novel environmental sounds (10%). The standard tones were pure tones of 1000 Hz and the deviant tones were pure tones of 1100 Hz. The novel sounds consisted of 100 unique environmental sounds from a database (Fabiani and Friedman, 1995), e.g. animal sounds (dog barking, bird singing), human sounds (coughs, laughs, sneezes), and other sounds (hammer ticking, water running). Novel sounds varied in duration between 161 and 403 ms. The duration of the standard and deviant tones were the mean duration of the novel sounds, 338 ms. The offset-to-onset interstimulus interval was 2.2 s. Tones were presented binaurally via ERTS at 75 dB through earphones (EarLink). Ten participants were instructed to respond as fast and accurately as possible after hearing a deviant target tone by pressing one of the buttons on the steering wheel (active oddball group). The other ten participants were instructed not to pay attention to the auditory stimuli (passive oddball group).

2.4. ERP recording

In order to measure ERPs in response to the secondary task, the electroencephalogram (EEG) was recorded during presentation of the auditory oddball task. The EEG was recorded from 32 Ag-AgCl electrodes at standard EEG recording positions. The reference electrode was placed on the right mastoid. Horizontal and vertical electro-encephalogram (EOG) was recorded with electrodes placed at the outer canthi of both eyes and below and above the left eye. The EEG and EOG were recorded with an online low-pass filter of 100 Hz and a high-pass filter of 0.15 Hz. Sample rate was 250 Hz.

2.5. Procedure

Participants were instructed to abstain from alcohol 24 h before the experiment and from caffeine containing substances for 12 h. Following the application of the EEG electrodes, participants were seated in a dimly lit room at 1.20 m from the computer screen. Participants were instructed to perform both tasks as good as possible, i.e. to drive as good as possible and to respond to the target stimuli of the oddball task as accurately and fast as possible (in the active oddball group). Participants were trained 5 min in driving in the DASS and 5 min in performing the oddball task. In both the passive and active oddball group three conditions were presented: performing the auditory novelty oddball task alone (single-task oddball), driving in the DASS alone (single-task driving), and performing the auditory novelty oddball task and driving simultaneously (dual-task). Each participant performed four 5-min blocks of the secondary oddball task alone, four 5-min blocks of the primary driving task alone, and four 5-min blocks of driving and performing the secondary auditory oddball task simultaneously, according to the time-schedule of Fig. 1.

2.6. Data analysis

2.6.1. Performance

For the active oddball group, mean reaction times in response to the deviant target stimuli of the secondary auditory oddball task, misses, and false alarms, were calculated for the single-task condition (oddball task alone) and the dual-task condition (oddball task and driving). Responses in the 150–1000 ms interval relative to the onset of the tones were regarded as valid responses. To investigate changes in attentional control, we also calculated the reaction time variability (SDRT) in the active oddball group.

Driving performance was analysed by calculation of the steering error during single-task (driving alone) and dual-task (driving and oddball task). The performance values of the driving task (steering error) and secondary oddball task (reaction times, SDRT, misses, and false alarms) were statistically analysed with repeated measurement analyses of variance (ANOVA) with condition (levels: single-task, dual-task) as factor, separately for the active oddball group and passive oddball group.

2.6.2. ERPs

ERP analyses were performed using Brain Vision Analyser software (Brain Products). The EEG data were filtered offline with a 0.16 Hz high-pass filter and a slope of 24 dB/oct and a 30 Hz low-pass filter with a slope of 24 dB/oct. Trials with false alarms (responses to the standard stimuli or novel stimuli) and misses (failed response to the deviant target stimuli), or invalid responses (responses out of the 150–1000 ms range) were removed. Artifacts were rejected and eye movements were corrected using the Gratton et al. (1983) method. The data were baseline corrected over the 100 ms interval preceding the stimulus presentation. Average ERP waveforms were calculated per stimulus (standard, deviant and novel) per condition (single-

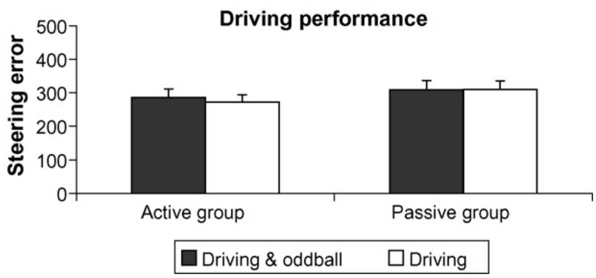

Fig. 2. Steering error in dual-task condition (driving and oddball task) and single-task condition (driving alone).

and dual-task). Difference waves were calculated by subtracting the average ERP for the standard tones from the average ERPs for the deviant tones and novel tones to analyse the ERP components. For analysis of the MMN, which is elicited in response to any detectable change in a stream of stimuli, the average amplitude from the deviant − standard difference wave in the epoch 196–236 ms after the onset of the stimulus at F4 was analysed in the passive oddball group. The P3a usually follows the MMN. The P3a is elicited by irrelevant novel stimuli and reflects the involuntary switching of attention towards these stimuli (Hillyard et al., 1975; for a review, see Friedman et al., 2001). The P3a was quantified as the average amplitude at FCz in the 325–375 ms post-stimulus interval from the novel − standard difference wave. The P3b is usually observed in response to deviant target stimuli and reflects attentional capacity. The P3b was calculated as the average amplitude at Pz in the 400–500 ms interval post-stimulus onset from the deviant − standard difference wave in the active oddball group. The reorienting negativity (RON) is a late negativity, which seems to reflect reorienting of attention after attention has been switched away from the task. The RON was quantified at FCz from the novel − standard difference wave as the average amplitude in the 490–550 ms post-stimulus interval.

The MMN, P3a, P3b and RON amplitudes were statistically evaluated with repeated measurement analyses of variance (ANOVA) with condition (levels: single-task, dual-task) as factor, separately for the active oddball group an the passive oddball group.

3. Results

3.1. Performance

3.1.1. Primary driving task: steering error

A repeated measures ANOVA was performed for steering error. Steering error did not differ between single-task and dual-task, not in the passive group, $F(1, 9) < 1$, n.s., nor the active group, $F(1, 9) = 1.21$, n.s. (see Fig. 2). Steering error was not affected by performing the secondary oddball task during driving.

3.1.2. Secondary oddball task: reaction times, misses and false alarms

A repeated measures ANOVA indicated that reaction times in the active oddball group did not differ significantly between single task (non-driving: oddball task alone) and dual-task (driving: oddball task and driving) performance, $F(1, 9) = 2.57$, n.s. reaction time variability (SDRT) was significantly larger in the dual-task condition compared to the single-task condition, $F(1, 9) = 7.58$, $p < .050$.

The proportion of misses during single-task (non-driving: oddball task alone) did not significantly differ from the proportion of misses during dual-task (driving: oddball task and driving), $F(1, 9) = 0.34$, n.s. The proportion of false alarms during the single-task condition (non-driving: oddball task alone) did not significantly differ from the proportion of false alarms during the dual-task condition (driving: oddball task and driving), $F(1, 9) = 1.12$, n.s. The results are summarized in Table 1.

3.2. ERPs

Fig. 3a shows the MMN in the grand average deviant − standard difference waveform for the driving and non-driving conditions for the passive oddball group. A repeated measures ANOVA indicated that the average amplitude of the MMN did not differ significantly between driving and non-driving in the passive oddball group, $F(1, 9) < 1$, n.s.

Fig. 3b shows the P3a and RON in the grand average novel − standard difference waveform for driving and non-driving conditions, separately for the passive group and the active group. The P3a is the large positive peak at 325–375 ms. A repeated measures ANOVA indicated that P3a amplitude was significantly reduced in the dual-task condition (driving and auditory oddball task) compared to single-task condition (non-driving: oddball task alone) for the passive oddball group, $F(1, 9) = 32.12$, $p < .001$. In the active oddball group, an effect in the same direction was not significant, $F(1, 9) = 3.66$, n.s. Following the P3a, a negativity can be observed at 490–550 ms. Repeated measures ANOVA indicated that this reorienting negativity (RON) did not significantly differ between single-task condition and dual-task condition in the passive oddball group, $F(1, 9) < 1$, n.s., or the active oddball group, $F(1, 9) = 3.60$, n.s.

Table 1
Reaction times (RT), reaction time variability (SDRT), misses and false alarms in dual-task condition (driving: driving and oddball task) and single-task condition (non-driving: oddball task alone)

	Driving	Non-driving
Mean reaction times	597.01 ms (S.D. = 130.66)	542.44 ms (S.D. = 103.89)
Reaction time variability (SDRT)	104.67 ms (S.D. = 23.21)	87.98 ms (S.D. = 18.21)
Mean proportion misses	0.0065 (S.D. = 0.0106)	0.0078 (S.D. = 0.0186)
Mean proportion false alarms	0.0009 (S.D. = 0.0015)	0.0036 (S.D. = 0.0079)

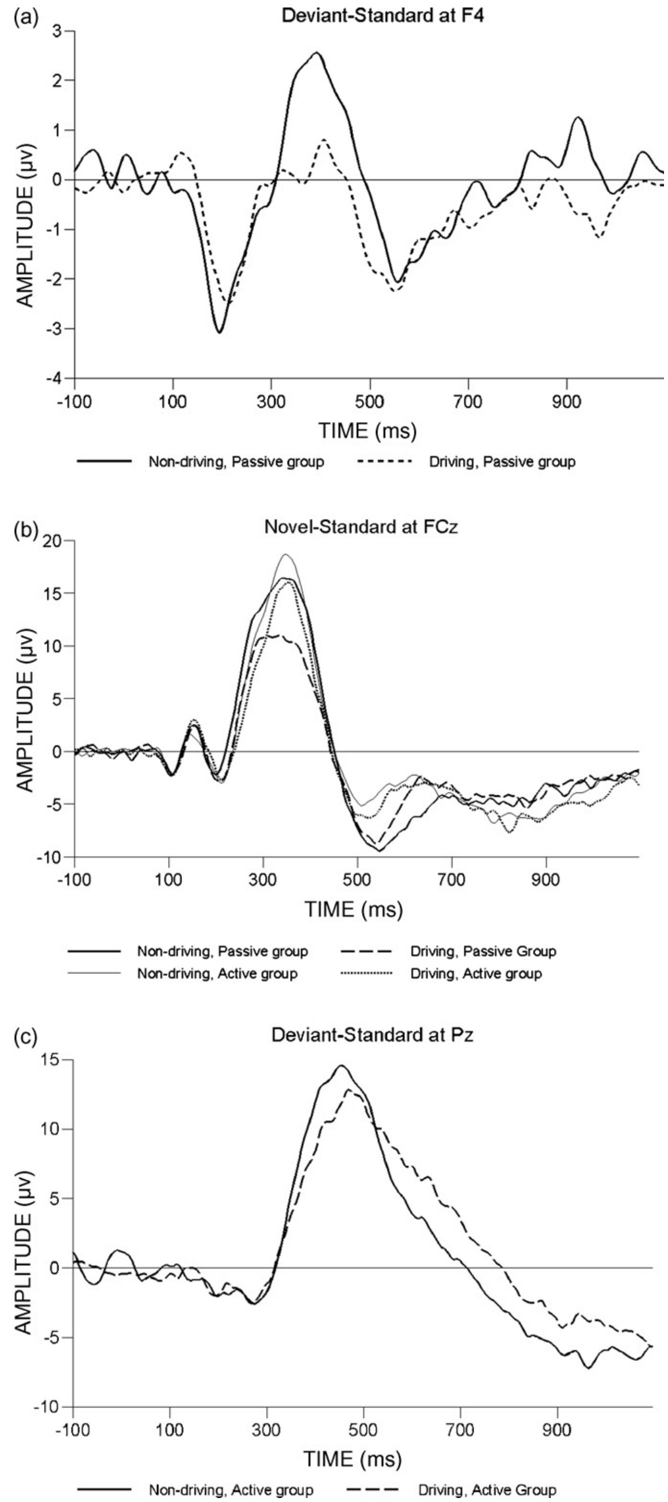

Fig. 3. (a) Grand average difference waveforms at F4 for single-task condition (non-driving: oddball task alone) and dual-task condition (driving: oddball task and driving) for the passive group. (b) Grand average difference waveforms at FCz for single-task condition (non-driving: oddball task alone) and dual-task condition (driving: oddball task and driving) for the passive group and active group. (c) Grand average difference waveforms at Pz for single-task condition (non-driving: oddball task alone) and dual-task condition (driving: oddball task and driving) for the active group.

The P3b was observed in the deviant − standard difference wave at Pz at 300–600 ms after stimulus onset for the active oddball group (see Fig. 3c). A repeated measures ANOVA revealed that the P3b for the active oddball group did not significantly differ between dual-task and single-task condition, $F(1, 9) = 2.96$, n.s.

4. Discussion

The goal of the present study was to investigate driver distraction by studying the effect of a secondary auditory task on simulated driving performance, using both performance measurements and the associated electric brain responses.

In this sample of healthy individuals driving performance was not affected by the secondary auditory events, not when they were completely irrelevant (although still possibly quite salient), nor when they were task-relevant (i.e. the deviant target stimuli in the active oddball group). One plausible explanation is that the simulated driving task and the auditory oddball task use separate channels and therefore, according to the multiple resource model, can be time-shared effectively (Wickens, 2002; Horrey and Wickens, 2002). Another explanation is that the secondary task may have been too simple.

However, recordings of brain activity showed that attention was less diverted towards the secondary oddball task during driving compared to non-driving. This was apparent in two ways. First, P3a to novels was reduced during driving in the passive oddball group, which suggests involuntary attention switching towards irrelevant stimuli of the secondary oddball task is reduced during driving to keep attention focused on the primary driving task. Second, reaction times to the auditory targets were more variable during driving, indicating a higher amount of occasional lapses of attention in the secondary auditory task. Admittedly, the idea of lapses of attention pertains to additional longer reaction times during driving relative to non-driving, which should have also resulted in longer mean reaction times during driving. One possibility is that the lapses of attention did predominantly occur during difficult driving passages (e.g. during a curve in the road), which were in turn followed by phases of enhanced alertness for target tones, resulting in relatively fast reaction times.

The results of the present study converge nicely with Lavie's theory of attention (Lavie et al., 1995, 2003, 2004), which postulates that distraction is reduced when the cognitive load is increased. Accordingly, we observed that the processing of irrelevant events was reduced during driving, relative to non-driving. This was specified in neurophysiological measures, i.e. the P3a that reflects automatic involuntary attention allocation towards irrelevant events.

The fact that our study was performed using a driving simulator is a limitation for the generalisation of our findings to real driving. Moskowitz and Fiorentino (2000) have argued that a valid driving simulator should represent the divided attention characteristics of driving, namely maintaining lane position (central tracking task) as well as searching for peripheral visual events (a visual search task that corresponds to monitoring the environment). In the current study, subjects only had to maintain lane position while performing an auditory task, but without the peripheral visual search task that is normally part of the DASS. A limitation of the Divided Attention Steering Simulator, with or without a modification such as ours, is that it does not involve other traffic or driving related tasks such as braking or responding to traffic lights. Still, precise steering is an important part of vehicle control, which should be protected in order to prevent accidents. Steering error has a strong resemblance to the standard deviation of the lateral position (SDLP) that is used in on-the-road driving studies during normal traffic. SDLP is considered as the golden standard to measure vehicle control (De Waard, 1996).

In conclusion, the current study shows that when performing a simple secondary task during driving, performance of the primary driving task and this secondary task are both unaffected. However, analysis of brain activity shows reduced cortical processing of irrelevant, potentially distracting stimuli of the secondary task during driving.

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