Die physiologische Erfassung des Fahrerzustandes:

Der Einfluss von Unaufmerksamkeit des Fahrers auf EEG Parameter und Verhaltensdaten

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Zusammenfassung

Trotz einer kontinuierlichen Abnahme an Verkehrstoten verunglücken jedes Jahr weltweit immer noch mehrere tausend Menschen auf den Straßen. Eine beträchtliche Zahl an Verkehrsunfällen wird durch Unaufmerksamkeit des Fahrers verursacht. Vermehrt versuchen Automobilhersteller, frühzeitig mentale Fahrerzustände zu detektieren, auf bevorstehende Gefahren aufmerksam zu machen oder durch Eingriffe in die Längs- bzw. Querregelung situationsbezogen zu reagieren. Die Elektroenzephalographie (EEG) stellt bei der Absicherung solcher Fahrerassistenzsysteme eine reliable und objektive Messung des kognitiven Aufmerksamkeitszustandes des Fahrers dar (de Waard, 1996). In der Leistung im Alpha-Band konnte hierzu im Labor bereits ein starker Zusammenhang zur Modalität der Aufmerksamkeit gefunden werden (Foxe et al., 1998; Cooper et al., 2003). Eine erfolgversprechende Alternative dazu scheinen Alpha-Spindeln zu sein, die kontinuierlich aus dem Spontan-EEG extrahiert werden können und auf deren Basis ein Maß abgeleitet werden kann, das eine im Vergleich zur Leistung im Alpha-Band erhöhte Robustheit gegenüber Augen-, Muskel- und technischen Artefakten aufweist (Simon et al., 2011).

Anhand eines Simulatorversuchs (Studie 1) wurden erst das Versuchsdesign und die Messtechnik validiert und anschließend das experimentelle Design auf zwei Realfeldversuche (Studien 2 und 3) übertragen. In Studie 1 zeigte sich eine signifikant höhere Alpha-Spindelrate während der Fahraufgabe mit zusätzlicher auditorischer Nebenaufgabe im Vergleich zur Fahraufgabe ohne Nebenaufgabe (Kontrollbedingung) und die signifikant niedrigste Spindelrate bei der Fahraufgabe mit visuo-motorischer Nebenaufgabe. Die Alpha-Spindeldauer war während der Fahraufgabe mit visuo-motorischer Nebenaufgabe signifikant kürzer als in den beiden anderen Bedingungen. Vor allem im Vergleich zu klassischen, aus Frequenzbändern extrahierten Leistungsmaßen aus dem EEG konnten für die beiden Alpha-Spindelparameter Rate und Dauer höhere Effektstärken gefunden werden. Während die Ergebnisse in der zweiten Studie in einem Realfeldversuch auf der Autobahn erfolgreich repliziert werden konnten, wurde in der dritten Studie in einem Car-Following Feldversuch auf einer abgesperrten Teststrecke der Zusammenhang zu Bremsreaktionszeiten hergestellt. Dabei zeigten sich signifikant längere Bremsreaktionszeiten, längere Alpha-Spindeldauern und eine höhere Alpha-Spindelrate während der zusätzlichen Bearbeitung einer auditorischen Nebenaufgabe. Mit fortlaufender Fahrtdauer konnten sowohl ein linearer Anstieg in der Bremsreaktionszeit als auch ein quadratischer Anstieg für die Alpha-Spindelrate festgestellt werden. Für eine Kombination von Alpha-Spindelparametern konnte innerhalb von dreiminütigen Zeitfenstern Unaufmerksamkeit mit einem Median-Klassifikationsfehler von 8% detektiert werden.

Es wird angenommen, dass ein Anstieg der Alpha-Spindelrate mit einer aktiven Hemmung der visuellen Informationsverarbeitung einhergeht und dies zu einer Verlängerung der Bremsreaktionszeiten führt.

Abstract

Despite a continuous decrease of road deaths, still a lot of accidents happen on roads all over the world. A substantial number of accidents are caused by driver inattention. Physiological and behavioural data are reliable and objective measures for detecting mental driver states (de Waard, 1996) and support the development of driver assistance systems in order to warn in time or intervene in critical situations. Electroencephalography (EEG), especially alpha activity, has proven to be sensitive to information processing states and has been used for describing different attention modalities (Foxe et al., 1998; Cooper et al., 2003). More promising measures seem to be based on alpha spindles derived from the EEG raw signal, which have proven to be more robust to ocular, muscular and technical artifacts in real road driving than alpha band power (Simon et al., 2011).

A simulator driving study (Study 1) was conducted to validate the experimental design and the testing method. Subsequently, the design was transferred to two real road driving studies (Study 2 and 3). In Study 1, driving with auditory secondary task showed a significantly higher alpha spindle rate compared to driving only and the lowest alpha spindle rate for driving with visuomotor secondary task. Alpha spindle duration was significantly shortened during driving with visuomotor secondary task. In Study 2, the experimental design was successfully transferred to real roads and the results observed in the driving simulation could be replicated. To show the correlation between alpha spindle parameters and brake reaction times, a car following task was conducted on a test track (Study 3) where participants had to react to emergency brakings of a lead car. With ongoing time-on-task, a linear increase was observed for brake reaction times and a quadratic increase for alpha spindle rate. Additionally, participants showed significantly prolonged brake reaction times, higher alpha spindle rate and longer alpha spindle duration during driving with auditory secondary task. Compared to traditional parameters like alpha band power, both alpha spindle parameters showed higher effect sizes and were more robust to muscular and technical artifacts. A combination of alpha spindle parameters yielded a median classification error of 8% in discriminating three-minute blocks of driving only from blocks of driving with auditory secondary task.

It is concluded that an increase of alpha spindle rate indicates an active inhibition of visual information processing according with prolonged brake reaction times.

1 Einleitung

In den letzten 40 Jahren nahm die Zahl der Verkehrstoten in Deutschland kontinuierlich ab (Abb. 1). Im Jahr 2011 starben trotzdem immer noch knapp 4.000 Menschen auf unseren Straßen (Statistisches Bundesamt, 2012), 2009 waren es EU-weit insgesamt 34.817 Verkehrstote (CARE, European road accident database, 2010). Unaufmerksamkeit des Fahrers stellt dabei eine häufige Unfallursache dar. Die NHTSA (National Highway Traffic Safety Administration) schätzt, dass zumindest 25% aller von der Polizei erfassten Verkehrsunfälle durch Unaufmerksamkeit des Fahrers verursacht werden, welche durch telefonieren, essen, trinken oder bedienen des Navigationssystems hervorgerufen wurde (Stutts et al., 2001). Klauer et al. (2006) erweiterten in ihren „Naturalistic Driving Studies" den Begriff der Unaufmerksamkeit und definierten vier Kategorien (Bearbeitung einer Nebenaufgabe, Schläfrigkeit, Unaufmerksamkeit auf die Straße, unspezifisches Abschweifen des Blickes). In einer Studie, in der Daten von 100 Fahrzeugen über ein ganzes Jahr aufgezeichnet wurden, brachten die Autoren 78% der aufgezeichneten Unfälle und 65% der Beinahe-Unfälle mit Unaufmerksamkeit des Fahrers in Beziehung. Die Bearbeitung von Nebenaufgaben (z.B.: kabellose Kommunikationsgeräte, interne oder externe Ablenkungen) hatte dabei den größten Einfluss.

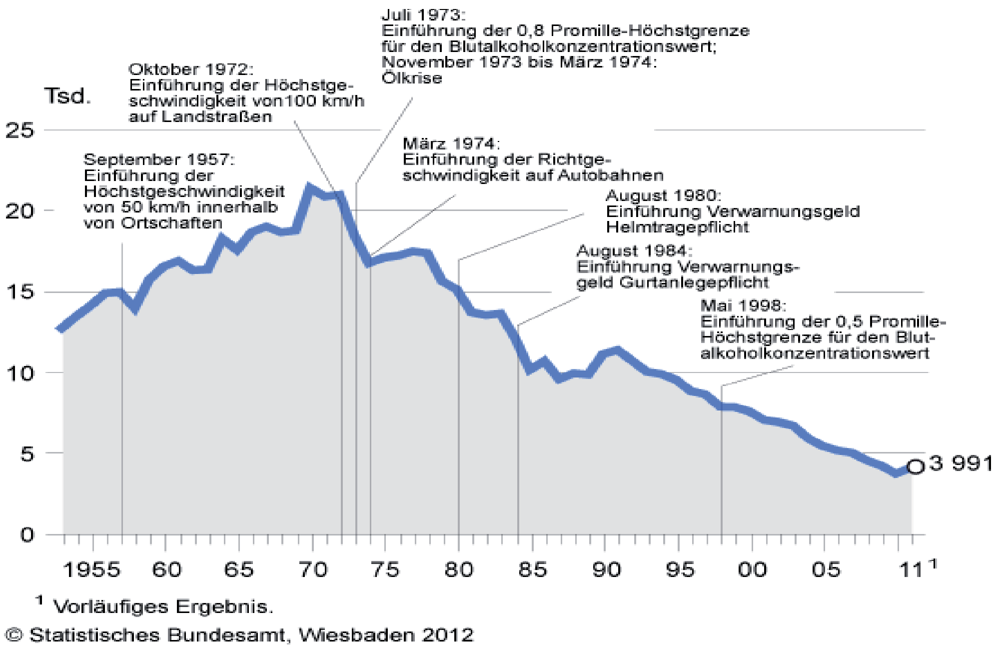

Abb.1: Entwicklung der Zahl der im Straßenverkehr Getöteten 1953-2011 (Statistisches Bundesamt, 2012)

1.1 Theoretischer Hintergrund

"Everyone knows what attention is. It is the taking possession of the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state..." (James, 1890).

In der Vergangenheit war das psychologische Konstrukt der Aufmerksamkeit Gegenstand intensiver und kontroverser Forschung. Broadbent (1958) nahm in seiner Filter-Theorie an, dass nur eine Informationsquelle zur gleichen Zeit in die tiefere Informationsverarbeitung gelangt und dass parallel wahrgenommene Information nicht verarbeitet werden kann. Deutsch und Deutsch (1963) gingen davon aus, dass die Information unabhängig der aktuellen Aufmerksamkeit parallel verarbeitet wird, jedoch nicht zu gleichen Teilen ins Bewusstsein gelangt. Kahnemann (1973) hingegen postulierte eine zentrale Verarbeitungseinheit mit begrenzten Aufmerksamkeitsressourcen, die auf unterschiedlich stark beanspruchende Aufgaben aufgeteilt werden. Im multiplen Ressourcenmodell von Wickens (1984) ist eine parallele Verarbeitung von Aufgaben unterschiedlicher Modalität, Verarbeitungsphase und Eingabe- bzw. Ausgabecode mit spezifischen Ressourcen möglich. Nach Wickens sollte simultane Informationsverarbeitung einer visuo-motorischen Nebenaufgabe mehr mit der großteils visuellen Fahraufgabe interferieren als beispielsweise eine auditorische Nebenaufgabe, da hier Aufgaben unterschiedlicher Modalität bearbeitet werden und die geteilte Aufmerksamkeit sich weniger stark überlagert.

Posner und Rafal (1987) führten erstmals die Begriffe „selektive Aufmerksamkeit", „geteilte Aufmerksamkeit" und „Vigilanz" ein. Dabei wird zwischen einer tonischen – also einem generellen Aktivierungsniveau – und einer phasischen Aktivierung – kurzfristige Aktivierungsschwankungen – unterschieden. Oft wird auch von Unaufmerksamkeit bzw. Ablenkung von einer Primäraufgabe gesprochen. Regan et al. (2011) trennen die beiden Begriffe Ablenkung und Unaufmerksamkeit. Sie definieren den Begriff der „Unaufmerksamkeit des Fahrers" als keine oder unzureichende Aufmerksamkeit auf Aktivitäten, die entscheidend für das sichere Führen eines Fahrzeuges sind. Neben aufgaben-bezogener und aufgaben-unbezogener Ablenkung definieren Regan et al. zusätzlich noch die weiteren Unterkategorien limitierte Aufmerksamkeit, falsche Priorisierung der Aufmerksamkeit, Vernachlässigung der Aufmerksamkeit und oberflächliche Aufmerksamkeit (siehe Abb. 2). Hier wird der Begriff der Ablenkung dem der Unaufmerksamkeit untergeordnet. Die in der vorliegenden Studie bearbeiteten visuomotorischen und auditorischen Nebenaufgaben sind nach der Definition von Regan der aufgaben-unbezogenen Ablenkung zuzuordnen. Die Aufmerksamkeit wird dabei beabsichtigt von der Fahraufgabe weg zu Aktivitäten gelenkt, die nicht zum sicheren Führen eines Fahrzeuges beitragen. Im Weiteren wird der Einfluss von Unaufmerksamkeit auf die Fahraufgabe erläutert.

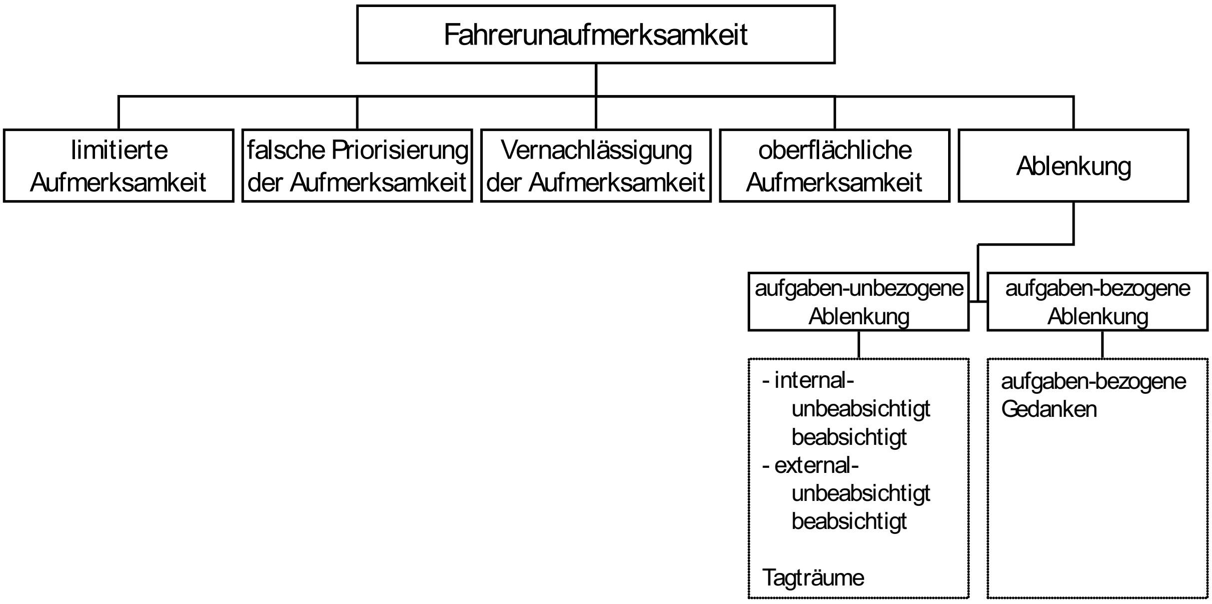

Abb.2: Taxonomie der Unaufmerksamkeit (Übersetzung durch den Autor. Original siehe Regan et al. (2011))

1.2 Unaufmerksamkeit beim Autofahren

Unaufmerksamkeit auf die Fahraufgabe bedingt durch eine auditorische oder visuomotorische Nebenaufgabe ist ein klassisches Beispiel von geteilter Aufmerksamkeit. Da die Fahraufgabe an sich eine komplexe, multimodale Aufgabe darstellt, gehen bereits einfache Nebenaufgaben mit einem erhöhten Unfallrisiko einher (Klauer et al., 2006; Olson et al., 2009). Olson et al. (2009) weisen darauf hin, dass Nebenaufgaben wie lesen oder schreiben immer eine Abwendung der visuellen Aufmerksamkeit von der Fahraufgabe mit sich ziehen. Im Gegensatz zu anderen epidemiologischen Studien führten Konversationen mit und ohne Freisprechanlage zu keiner Erhöhung des Unfallrisikos, wobei die kognitive Beeinträchtigung in dieser Studie nicht gemessen wurde. Bei Nutzfahrzeugen wurden 71% der Unfälle und 46% der Beinahe-Unfälle mit Unaufmerksamkeit des Fahrers in Verbindung gebracht. In einer PKW-Studie von Klauer et al. (2006) berichteten die Autoren von 78% der Unfälle und 65% der Beinahe-Unfälle, bei denen Unaufmerksamkeit als Ursache festgestellt wurde. Da diese Studien Daten in Fahrzeugen erheben, die tagtäglich am Verkehr teilnehmen, weisen die Ergebnisse eine hohe ökologische Validität auf. Der Aspekt der kognitiven Beeinträchtigung kann mittels Videodaten, Fahrzeugdaten oder subjektiven Nachbefragungen allerdings nicht erhoben werden. In zahlreichen Studien konnte eine verlängerte Reaktionszeit bei Telefonieren während der Fahrt gezeigt werden (für eine Übersicht siehe Horrey & Wickens, 2006). Internale Aufmerksamkeit, die sich auch in Form von Tagträumen äußert und im Fahrkontext als „Highway-Hypnosis" auftritt (Wertheim, 1991), führt beim so genannten „Looked-but-failed-to-see"-Phänomen häufig zu Unfällen (Herslund, 2003). Kognitive Ressourcen müssen oft auf parallele Prozesse aufgeteilt werden, und so kann nicht jede Information mit der gleichen Qualität weiterverarbeitet werden. In Regionen über dem präfrontalen und dem parietalen Kortex wird die aktuell eingehende Information bewertet, und es wird entschieden, mit welchem Aufwand diese weiterverarbeitet wird (Birbaumer & Schmidt, 2010). Bei Priorisierung von aufgaben-unbezogener Information werden Ressourcen von der Primäraufgabe abgezogen und auf eine Nebenaufgabe verlagert.

Bowyer et al. (2009) haben den Einfluss von Gesprächen während der Beobachtung einer Fahrszene mittels EMG in einer simulierten Umgebung untersucht. Eine Konversation über die Freisprecheinrichtung führte zu einer Reduzierung der Amplitude von ereigniskorrelierten Potentialen im visuellen Kortex sowie im rechten Parietallappen und zu Verzögerungen in der Reaktionszeit. In einer angrenzenden Arbeit untersuchten Hsieh et al. (2009) mittels fMRI ein fronto-parietales Netzwerk, das Effekte von Konversationen auf die visuelle Informationsverarbeitung zeigte. Da die Mobilität von stationären Messungen wie MEG oder fMRI begrenzt ist, wurden im Fahrkontext verschiedenste Methoden zur Beschreibung von kognitiven Aufmerksamkeitszuständen herangezogen. Im folgenden Kapitel soll vor allem die Elektroenzephalographie (EEG) näher betrachtet werden.

1.3 Methoden zur Erfassung von Unaufmerksamkeit im Fahrzeug

Neben Verhaltensbeobachtungen und Reaktionszeitmessungen eignet sich das EEG besonders für die Erfassung des Fahrerzustandes. Vor allem die reliable, objektive und zeitlich hoch aufgelöste Aufzeichnung des Signals sprechen für eine Anwendung im Kontext des Autofahrens. Sowohl in Simulatoren als auch im Fahrzeug hat sich das EEG bereits als geeignete Messmethode bewährt (Papadelis, 2007; Schmidt et al., 2009; Brookhuis & de Waard, 2010).

Im EEG werden speziell Schwingungen im Alpha-Band (8-12 Hz) mit Aufmerksamkeit in Verbindung gebracht. Es wird angenommen, dass eine hohe Alpha-Aktivität mit einer Hemmung der visuellen Informationsverarbeitung einhergeht. Dabei ist noch nicht abschließend geklärt, ob es sich um eine Hemmung von für die Aufgabe irrelevante Bereiche handelt (Jokisch & Jensen, 2007; Klimesch et al., 2007) oder ob die Hemmung unabhängig von der Aufmerksamkeitsrichtung ist (Ray & Cole, 1985). Foxe et al. (1998) beobachteten Effekte der Aufmerksamkeit auf parieto-okzipitale Hirnaktivität (~10 Hz). ProbandInnen mussten abhängig von Schlüsselwörtern ihre Aufmerksamkeit auf eine Modalität von bimodal dargebotenen Reizen richten. In Erwartung auditorischer Reize zeigte sich eine erhöhte parieto-okzipitale Aktivität im Vergleich zu visuellen Reizen. Diese Ergebnisse sprechen für eine aktive Hemmung der eingehenden visuellen Information in Erwartung auditorischer Reize. Einen weiteren Befund für den Zusammenhang zu visueller Informationsverarbeitung lieferten van Dijk et al. (2008). MEG-Messungen in einem Schwellwertexperiment zeigten erhöhte parieto-okzipitale Aktivität einhergehend mit einer reduzierten visuellen Diskriminierungsfähigkeit. Hier wird angenommen, dass für die visuelle Wahrnehmung bedeutende Bereiche über dem parieto-okzipitalen Kortex gehemmt werden. Auch Cooper et al. (2003) fanden einen klaren Zusammenhang von Alpha-Aktivität mit der Richtung der Aufmerksamkeit (external und internal) und mit der Aufgabenschwierigkeit. Bei internaler Aufmerksamkeit und bei gesteigerter Schwierigkeit zeigte sich eine erhöhte Alpha-Amplitude über weite Teile des Kortex.

Betrachtet man die Literatur zur Leistung im Gamma-Band, so lassen sich einige Studien finden, die einen Zusammenhang zwischen Gamma-Aktivität und selektiver Aufmerksamkeit postulieren (Fell et al., 2003; Landau et al., 2007; Jensen et al., 2007). Visuelle Informationsverarbeitung sowie Wahrnehmungsmechanismen werden mit einer vermehrten, synchron auftretenden neuronalen Aktivität in einem Frequenzbereich zwischen 30 und 100 Hz in Verbindung gebracht. Gerichtete Aufmerksamkeit auf einen Stimulus ruft eine höhere Gamma-Aktivität hervor als ein Ignorieren des Reizes (Müller et al., 2000). Gruber et al. (1999) fanden eine Veränderung der Gamma-Aktivität kontralateral zu einer Verschiebung der Aufmerksamkeit auf einen rotierenden Reiz. Diese Befunde wurden unter hoch kontrollierten Bedingungen im Labor gezeigt. Es bleibt abzuwarten, ob diese Ergebnisse in einem ökologisch valideren Setting mit einer höheren Anzahl an Umgebungseinflüssen und komplexeren Aufgabenstellungen, wie beispielsweise einer Fahraufgabe, wiederholt werden können.

Aufgrund der gegebenen Anfälligkeit auf Artefakte bei der Erhebung des Spontan-EEG im Feldversuch scheint eine Extraktion von Parametern aus dem Alpha-Band mittels vorgegebener Kriterien eine viel versprechende Alternative für die Anwendung im Fahrzeug. Die so genannten Alpha-Spindeln, sinusförmige Muster aus dem Spontan-EEG, werden im folgenden Abschnitt näher erklärt.

1.4 Alpha-Spindeln als Indikatoren für Unaufmerksamkeit im EEG

Bereits eine visuelle Inspektion des Spontan-EEGs von Probanden, die ihre Augen geschlossen haben, lässt vor allem auf parieto-okzipitalen Elektroden deutlich sinus-förmige Schwingungen erkennen. Diese spektralen Mikrostrukturen werden als Alpha-Spindeln bezeichnet. Sie haben ihre höchste Leistung in einem schmalen Frequenzband innerhalb des vordefinierten Alpha-Bandes und sind durch das charakteristische Zu- und Abnehmen des Alpha-Rhythmus gekennzeichnet (Shaw, 2003). Simon et al. (2011) berichteten eine Methode mit der eine automatische Detektion der Spindeln inklusive der Parameter Alpha-Spindelrate (Häufigkeit pro Minute), Dauer, Frequenz und Amplitude möglich ist. Neben einem müdigkeits-bedingten Langzeiteffekt auf die Alpha-Spindelrate (Simon et al., 2011) zeigen sich auch spontane Fluktuationen von phasischen kognitiven Prozessen. Es wird angenommen, dass hier kurzfristige Aufmerksamkeitsschwankungen abgebildet werden, die durch externale und internale Prozesse beeinflusst werden.

Auch wenn die Alpha-Aktivität zu einem großen Teil im Kortex generiert wird (Bollimunta, 2011), wird angenommen, dass die Alpha-Spindeln durch eine Interaktion von thalamischen Schaltzellen und dem Nucleus reticularis thalami beeinflusst werden. Dieses „thalamo-kortikale Zwischenspiel" dient als Wächter für einkommende Information und gewichtet diese für die weitere Verarbeitung (Pfurtscheller, 2003). Der Thalamus spielt in der Lenkung der Aufmerksamkeit eine wichtige Rolle, in dem er die Abstimmung zwischen retikulärer Aktivierung und kortikalen Verarbeitungsprozessen übernimmt (Cohen, 1993). Dafür spricht eine weitreichende, komplexe Vernetzung von Thalamus und cerebralem Kortex auf anatomischer, phylogenetischer und funktionaler Ebene (Reinoso-Suarez, 2010). Sowohl afferente als auch efferente Bahnen des präfrontalen Kortex selektieren aktuell wichtige Teilinformationen. Beispielsweise kann kurzfristig nur akustische Information über den Nucleus geniculatum mediale passieren, bei gleichzeitiger Blockade von visueller Information im Nucleus geniculatum laterale (Birbaumer & Schmidt, 2010). Selektive Aufmerksamkeit macht von diesen Aufmerksamkeitsmechanismen Gebrauch, um eingehende Information zu gewichten. So können Ressourcen für die Verarbeitung von eingehender visueller Information für eine priorisierte auditorische Information abgezogen werden.

Alpha-Spindeln stellen daher ein erfolgversprechendes Maß für die Detektion von kurzfristigen Abwendungen der Aufmerksamkeit von der Fahraufgabe dar. Die höhere Robustheit gegenüber technischen-, Augen- und Muskelartefakten ermöglicht zudem einen praktikablen Einsatz in realen Fahrsituationen.

1.5 Einfluss von Unaufmerksamkeit auf Bremsreaktionen

Um den Einfluss von gehemmter visueller Informationsverarbeitung auf Bremsreaktionszeiten zu bestimmen, muss der exakte Ablauf zwischen dem Erscheinen eines Stimulus bis zum Einsetzen der Bremswirkung untersucht werden. Burkhardt (1985) berichtet von einer durchschnittlichen Reaktionszeit von 640 ms ab der Fixation eines Objektes bis hin zur Berührung des Bremspedals. Wie in Abbildung 3 dargestellt, wird die Muskelbewegung des rechten Beines in einem Intervall von 220 ms (2.Perzentil) über 450 ms (50.Perzentil) bis 580 ms (98.Perzentil) initiiert. Speziell in diesem Teil sollten sich die Reaktionszeiten von unaufmerksamen Fahrern verlängern. Strayer (2006) untersuchte in einer Fahrfolgeaufgabe Bremsreaktionszeiten, Time-to-collision und Abstände zwischen den beiden Fahrzeugen bei telefonierenden (mit und ohne Freisprechanlage) und alkoholisierten Fahrern (Blutalkoholkonzentration von 0,8‰). Für beide Gruppen zeigte sich ein deutlich verändertes Fahrverhalten im Vergleich zur Kontrollgruppe der nüchternen, nicht abgelenkten Fahrer. Telefonierende Fahrer reagierten langsamer (Reaktionszeit: Kontrollbedingung = 777 ms, Telefon = 849 ms, Alkohol = 779 ms), hielten größere Abstände zum vorausfahrenden Fahrzeug (Abstand zum vorausfahrenden Fahrzeug: Kontrollbedingung = 27,4 m, Telefon = 28,4 m, Alkohol =26,0 m) und hatten höhere Unfallwahrscheinlichkeiten (Time-to-collision: Kontrollbedingung = 8,5 s, Telefon = 8,1 s, Alkohol = 8,0 s). Alkoholisierte Fahrer dagegen zeigten ein deutlich aggressiveres Fahrverhalten, dennoch bescheinigten die Autoren telefonierenden und alkoholisierten Fahrern ein vergleichbares Unfallrisiko.

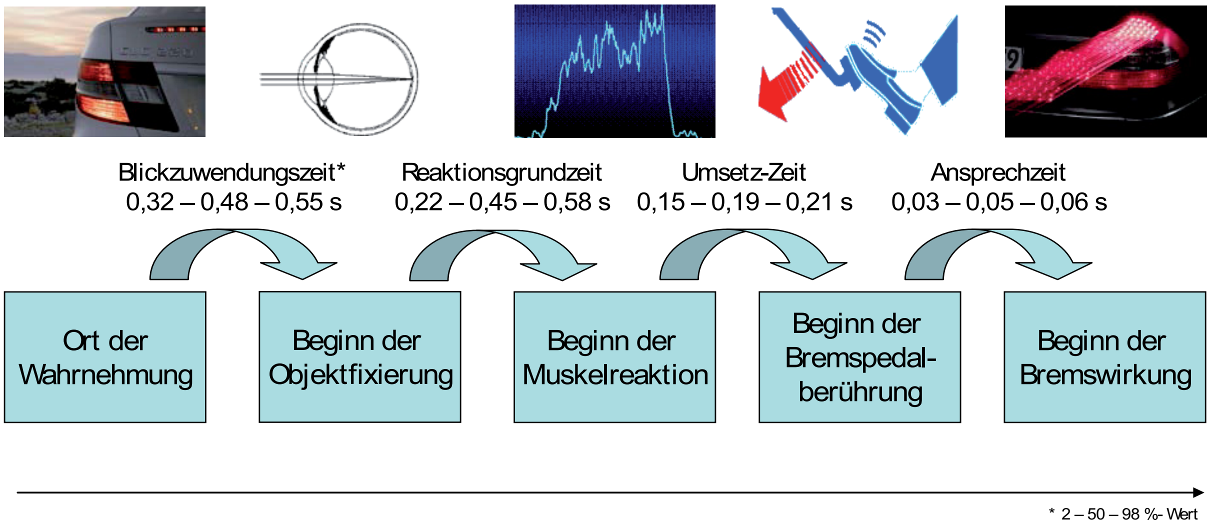

Abb. 3: Handlungsablauf einer Bremsreaktion (visualisiert anhand der Daten von Gratzer, 2009)

1.6 Fragestellungen

Um die Zahl an Verkehrsunfällen, die durch Unaufmerksamkeit bedingt sind zu reduzieren, müssen unaufmerksame Fahrer aufgrund verlangsamter Reaktionszeiten frühzeitig gewarnt oder aktiv unterstützt werden. Die Zielstellung dieser Arbeit beinhaltet daher eine robuste, objektive und echtzeitfähige Zustandserkennung von unaufmerksamen Fahrern in realen Fahrsituationen. Hierbei sollen kurzfristige Aufmerksamkeitsschwankungen mit physiologischen- und Verhaltensdaten detektiert werden. Alpha-Spindeln im EEG versprechen eine valide Beschreibung von kognitiven Fahrerzuständen und haben sich für den Einsatz im Fahrzeug bewährt. Im Simulator gezeigte Ergebnisse sollen bei gleichem Versuchsdesign in einer Realfeldstudie repliziert werden und anschließend soll der Zusammenhang zu Verhaltensdaten hergestellt werden. Aus diesen Anforderungen lassen sich folgende Fragestellungen ableiten:

a) Ist es möglich, mit Alpha-Spindeln unaufmerksame Fahrerzustände zu beschreiben? Haben diese Maße im Vergleich zu traditionellen Leistungsmaßen aus dem Alpha-Band eine vergleichbare oder bessere Effektstärke bei der Unterscheidung von Fahren mit auditorischer Nebenaufgabe, Fahren mit visueller Nebenaufgabe und Fahren ohne Nebenaufgabe?

b) Lassen sich die im Simulatorversuch gewonnenen Ergebnisse auf Realfeldversuche übertragen? Zeigt sich der Einfluss einer Nebenaufgabe auch direkt in veränderten Bremsreaktionszeiten auf ein vorausfahrendes Fahrzeug?

c) Können Fahrerzustände über 3-Minuten-Abschnitte auf der Basis von EEG-Daten klassifiziert werden? Können unaufmerksame von aufmerksamen Fahrerzuständen unterschieden werden?

2 Studien

Um verschiedene Parameter für die Fahrerzustandserkennung zu untersuchen, wurde erst ein Simulatorversuch (Studie 1) durchgeführt. Hier wurden die Parameter für die beiden weiteren Studien festgelegt. Anschließend wurde das experimentelle Design auf einen Feldversuch (Studie 2) übertragen. Der Einfluss der Unaufmerksamkeit auf das Bremsverhalten wurde in einer Fahrfolgeaufgabe auf einer abgesperrten Teststrecke untersucht (Studie 3). Für die drei Studien übernahm der Autor die Gestaltung des experimentellen Designs, die Planung, die Durchführung und die statistische Auswertung der gesamten Studie.

Studie 1: Einleitung (60%); Methodik (80%); Datenerhebung (100%); Auswertung (75%); Diskussion (60%); Dokumentation (80%)

Studie 2: Einleitung (60%); Methodik (50%); Datenerhebung (50%); Auswertung (75%); Diskussion (60%); Dokumentation (80%)

Studie 3: Einleitung (60%); Methodik (80%); Datenerhebung (50%); Auswertung (75%); Diskussion (60%); Dokumentation (80%)

2.1 Studie 1: Alpha-Spindeln als neurophysiologische Korrelate für Aufmerksamkeitsabwendung in einer Simulatorstudie

Ziel der ersten Studie ist eine Beschreibung von neurophysiologischen Korrelaten zu Ablenkung während der Fahrt. Hierzu wurden hoch robuste Parameter aus dem Spontan-EEG extrahiert, so genannte Alpha-Spindeln. Zusätzlich wurden klassische Maße wie die Leistung im Alpha- bzw. im Gamma-Band bestimmt. 28 ProbandInnen führten in einer simulierten Tagfahrt mit zwei ablenkenden Nebenaufgaben (visuo-motorisch, auditorisch) Vollbremsungen auf plötzlich auftauchende Stopp-Schilder und auf unangekündigt auf rot umschaltende Ampeln durch.

Für die Alpha-Spindelrate konnten im Vergleich zur Fahraufgabe ohne Nebenaufgabe (Kontrollbedingung) während der auditorischen Nebenaufgabe signifikant höhere und während der visuo-motorischen Nebenaufgabe signifikant niedrigere Werte gefunden werden. Die Dauer der Alpha-Spindeln war während der visuo-motorischen Nebenaufgabe signifikant verkürzt. Die Ergebnisse sprechen für einen Zusammenhang von Alpha-Spindeln mit aktiver Hemmung der visuellen Informationsverarbeitung. Die teilweise Verlagerung der Aufmerksamkeit weg von der Fahraufgabe hin zu auditorischen bzw. visuo-motorischen Nebenaufgaben hatte einen signifikanten Einfluss auf die Spindelrate. Im Vergleich zu klassischen, aus dem EEG gewonnenen Maßen, wie die Leistung im Alpha-Band, zeigten sich Alpha-Spindeln robuster gegenüber Artefakten, was mitunter zu höheren Effektstärken führte, die in Zukunft eine genauere Beschreibung des aktuellen Fahrerzustandes erlauben.

2.2 Studie 2: Fahrerzustandserkennung – Neurophysiologische Korrelate für Aufmerksamkeitsabwendungen in einer Realfahrstudie

Diese Studie wurde durchgeführt um robuste Parameter im EEG zu erforschen, die Unaufmerksamkeit indizieren und gleichzeitig für den Einsatz auf realen Straßen geeignet sind. Dazu führten 40 ProbandInnen neben der Fahraufgabe aufgaben-unbezogene Zweitaufgaben (visuo-motorisch, auditorisch) durch. Um die Sicherheit im öffentlichen Straßenverkehr zu gewährleisten, wurden während der Messung der Abstandsregeltempomat aktiviert, die Versuchsfahrzeuge mit Zweitpedalerie ausgestattet, die Beifahrer speziell geschult und die ProbandInnen zusätzlich instruiert, während der Aufgaben nicht zu überholen. Die visuomotorische Nebenaufgabe bestand aus einer visuellen Detektionsaufgabe, die auf einem Display auf der Höhe des Navigationssystems dargestellt wurde. Bei der auditorischen Nebenaufgabe waren die ProbandInnen instruiert, einem Hörbuch zu folgen, kontinuierlich Schlüsselwörter zu detektieren und am Ende jedes Abschnitts eine inhaltliche Frage zu beantworten.

Im EEG konnten eine signifikant höhere Alpha-Spindelrate während der auditorischen Nebenaufgabe und eine signifikant geringere Spindelrate für die visuo-motorische Nebenaufgabe im Vergleich zur reinen Fahraufgabe gezeigt werden. Für die visuo-motorische Nebenaufgabe konnten signifikant kürzere Alpha-Spindeldauern im Vergleich zur reinen Fahraufgabe und zur auditorischen Nebenaufgabe beobachtet werden.

Es wird angenommen, dass der Einfluss der Nebenaufgaben auf die Alpha-Spindeln durch eine Verlagerung der Aufmerksamkeit abhängig von der Modalität bedingt ist. Die Ergebnisse gehen mit der Annahme einher, dass Alpha-Spindeln den Grad der visuellen Informationsverarbeitung repräsentieren. Im Vergleich zur Leistung im Alpha-Band zeigten sich die Alpha-Spindelparameter robuster gegenüber technischen- und Muskel-Artefakten. Sie zeigten auch höhere Effektstärken für den Unterschied zwischen den Bedingungen mit Nebenaufgaben und der reinen Fahraufgabe, was eine präzisere und effizientere Beschreibung verschiedener Fahreraufmerksamkeitszustände im Fahrzeug ermöglicht.

2.3 Studie 3: Analyse und Einzelfall-Klassifikation von Alpha-Spindeln für verlängerte Bremsreaktionszeiten während auditorischer Ablenkung in einer Realfahrstudie

Ablenkung von der Fahraufgabe ist eine häufige Unfallursache. In dieser Studie sollte der Einfluss von auditorischen Nebenaufgaben auf mentale Fahreraufmerksamkeitszustände beschrieben werden. 20 ProbandInnen nahmen an einer Studie auf einer abgesperrten Teststrecke teil, in der die Teilnehmer auf abrupte Bremsungen eines vorausfahrenden Fahrzeuges reagieren mussten. Sowohl Leistungsmaße (Reaktionszeiten) als auch die Hirnaktivität (EEG Alpha-Spindeln) der ProbandInnen wurden analysiert, um abgelenkte Fahrerzustände zu beschreiben. Zusätzlich wurde ein Klassifikationsansatz untersucht, um festzustellen, ob Alpha-Spindeln den aktuellen Aufmerksamkeitszustand des Fahrers in einem 3-Minuten-Fenster vorhersagen können.

Die Ergebnisse wiesen eine erhöhte Reaktionszeit und eine erhöhte Alpha-Spindelrate bei der Fahraufgabe mit auditorischer Nebenaufgabe verglichen mit der Fahraufgabe ohne Nebenaufgabe auf. Auch mit fortlaufender Fahrtdauer verlängerten sich die Bremsreaktionszeiten, und die Alpha-Spindelrate stieg signifikant an. Für die Klassifikation zeigte eine Kombination der vier Alpha-Spindelparameter einen Median-Klassifikationsfehler von 8% für die Unterscheidung der Fahraufgabe mit und ohne auditorischer Nebenaufgabe. Es wird angenommen, dass die verlangsamten Reaktionszeiten während gesteigerter Beanspruchung durch eine auditorische Nebenaufgabe mit einer erhöhten Alpha-Spindelrate einhergehen. Dies ermöglicht eine objektive Beschreibung von Fahreraufmerksamkeitszuständen in Realfahrstudien, ohne dabei die ProbandInnen introspektiv befragen zu müssen.

3 Allgemeine Diskussion und Ausblick

Die im Rahmen dieser Arbeit durchgeführten Studien zeigten durchweg konsistente Ergebnisse bezüglich der Alpha-Spindel-Daten und belegen einen starken Zusammenhang mit der Bearbeitung von Nebenaufgaben parallel zur Fahraufgabe. Sowohl im Fahrsimulator als auch im Fahrzeug erwiesen sich Alpha-Spindeln in Kombination mit einer Online-Artefakt-Korrektur als äußerst robustes Maß für die Fahrerzustandserkennung.

Während der Bearbeitung einer auditorischen Nebenaufgabe und einer damit einhergehenden Internalisierung der Aufmerksamkeit konnte eine erhöhte Alpha-Spindelrate festgestellt werden. Dagegen zeigte sich für die Bearbeitung einer visuo-motorischen Nebenaufgabe, die mit einer Erhöhung der Aufnahme von externalen visuellen Reizen einhergeht, eine signifikant geringere Alpha-Spindelrate im Vergleich zur Fahraufgabe ohne Nebenaufgabe. Veränderungen in der Aufmerksamkeitsmodalität bewirkten Niveauunterschiede in der Alpha-Spindelrate in den jeweiligen 3-minütigen Aufgabenblöcken, die den ProbandInnen abwechselnd vorgegeben wurden. Es wird angenommen, dass diese kurzfristigen Fluktuationen den aktuellen Grad der visuellen Informationsverarbeitung anzeigen. Eine Erhöhung der Alpha-Aktivität wird mit einer Erhöhung der aktiven funktionalen Hemmung beteiligter Areale und einer dadurch eingeschränkten visuellen Informationsverarbeitung in Verbindung gebracht. Diese Ergebnisse decken sich mit vorangegangen Studien, in denen sich die Alpha-Aktivität ebenfalls mit der Modalität der zu bearbeitenden Aufgabe veränderte (Foxe et al., 1998; Cooper et al., 2003; van Dijk et al., 2008).

Unabhängig von der Beeinflussung durch Nebenaufgaben zeigte sich auch ein Zeiteffekt für das Alpha-Spindelniveau. Mit zunehmender Fahrtdauer nahm die Alpha-Spindelrate signifikant zu. Es wird angenommen, dass die aufgaben-bezogene Müdigkeit mit der Dauer der Fahrt steigt, dadurch weniger Ressourcen zur Verfügung gestellt werden und gleichzeitig die allgemeine visuelle Informationsverarbeitung aktiv gehemmt wird. Dies passt zu Ergebnissen aus vorangegangenen Studien zur langfristigen Entwicklung von Alpha-Spindeln bei Realfahrten (Schmidt et al., 2009; Simon et al., 2011). In den weiteren extrahierten Parametern konnten keine ähnlichen Effektstärken gezeigt werden.

Um eine validere Aussage über die in Studie 1 im Fahrsimulator erzielten Ergebnisse machen zu können, wurde das experimentelle Design für die Studie 2 ins Fahrzeug übertragen. Die Ergebnisse im Fahrzeug zeigten eine deutlich geringere Zunahme der Alpha-Spindelrate im

Vergleich zum Simulator. Dieses bekannte Phänomen der schneller eintretenden Müdigkeit in Simulatorversuchen wurde auch bereits von Philip et al. (2005) erwähnt. Es wird angenommen, dass eine verringerte ökologische Validität und ein nicht mit Konsequenzen behaftetes Unfallrisiko mit einer allgemeinen Verringerung der Aktivierung einhergehen. Die Autoren schlussfolgerten, dass eine Müdigkeitsdetektion im Simulator möglich sei, die erwartete Effektstärke jedoch im Vergleich zu realen Fahrstudien angepasst werden müsste. Ähnliche Schlussfolgerungen können aus den in diesen beiden Studien erhobenen Ergebnissen gezogen werden.

In der Literatur wird oft von verstärkt auftretenden Alpha-Spindeln in parietalen Regionen (Schmidt et al., 2009) oder parieto-okzipitalen Regionen (Schmidt et al., 2000) berichtet. Die absolute Häufigkeit von Alpha-Spindeln in der Online-Messung sowie die häufig bessere Sichtbarkeit der Oszillationen sprechen für eine verstärkte funktionale Bedeutung in diesen Regionen. In dieser Arbeit konnte aber gezeigt werden, dass die Verteilung von Alpha-Spindeln abhängig von der gewählten Referenz ist. Drei verschiedene Referenzen (Elektrode Cz, Common Average, linked Mastoid) ergaben zwar eine unterschiedliche absolute Anzahl an detektierten Spindeln für definierte Kanalgruppen. Eine anschließende z-Transformation der Werte zeigte allerdings eine identische Beeinflussung durch die Bearbeitung von Nebenaufgaben, unabhängig von der gewählten Referenz. Der Vergleich der Referenzen wies eine breite Verteilung der Effekte auf, deutet also auf einen ganzheitlichen Einfluss der Bedingungen auf die Alpha-Spindelrate hin. Auch die Reduktion von 32 Elektroden in der Simulatorstudie auf 16 Elektroden in der Fahrstudie zeigte keinen Einfluss auf die Ergebnisse. Dies lässt auf einen allgemeinen Einfluss der Alpha-Spindeln über den gesamten Kortex, ausgehend von einer oder mehrerer interaktiver Quellen, schließen. Es wird davon ausgegangen, dass die Alpha-Spindeln aus einem Zusammenspiel von thalamischen Schaltzellen und dem Nucleus reticularis thalami entstehen (Pfurtscheller, 2003). Die genaue Herkunft kann durch diese EEG-Studien allerdings nicht erklärt werden. Hierfür müssten bildgebende Verfahren wie beispielsweise die funktionelle Magnetresonanztomographie (fMRT) eingesetzt werden.

Für die Alpha-Spindeldauer zeigte die Fahraufgabe mit visueller Nebenaufgabe einen signifikanten Unterschied zur Fahraufgabe ohne Nebenaufgabe und zur Fahraufgabe mit auditorischer Nebenaufgabe. Sowohl im Simulator als auch im Fahrzeug zeigten sich im Mittel kürzere Alpha-Spindeln. Als Erklärung hierfür kann die erhöhte visuelle Aufmerksamkeit auf zwei parallel dargebotene Aufgaben (Fahraufgabe, visuelle Detektionsaufgabe) genannt werden, die einen ständigen Wechsel der Aufmerksamkeit erforderte. Durch das permanente Abscannen der beiden Inhalte ergab sich eine stark erhöhte visuelle Beanspruchung mit einem hohen

Grad an visueller Informationsverarbeitung. Dieser Effekt wurde sowohl in einer geringeren Alpha-Spindelrate als auch in einer verkürzten gemittelten Alpha-Spindeldauer sichtbar.

Die restlichen beiden Alpha-Spindelparameter Frequenz und Amplitude zeigten keine Sensitivität gegenüber den untersuchten Bedingungen. Für die Alpha-Spindelfrequenz konnte allerdings mit steigender Fahrtdauer eine Verschiebung des berechneten Frequenz-Peaks der detektierten Alpha-Spindeln in Richtung Theta-Aktivität gefunden werden. Eine polynomiale Trendanalyse zeigte eine lineare Verringerung der Frequenz mit ansteigender Fahrtdauer. Diese Frequenzverschiebung kann auch beim Übergang vom Wachzustand hin zur Schläfrigkeit beobachtet werden (Klimesch, 1999).

Im Vergleich zu traditionellen EEG-Maßen wie Leistung im Alpha-Band, konnten die in dieser Studie extrahierten Alpha-Spindelparameter eine höhere Sensitivität bezüglich des Fahrens mit und ohne Nebenaufgabe aufweisen. Durch die Detektion des Frequenzmaximums in einem vordefinierten Frequenzband und einer zusätzlichen Definition von Qualitätskriterien wird die Validität der gemessenen Alpha-Aktivität erhöht. Zusammen mit einer Artefakt-Korrektur konnte weitestgehend sichergestellt werden, dass tatsächlich neurologische Muster interpretiert werden. Dies spielt vor allem bei der Übertragung des experimentellen Designs in die reale Fahrumgebung eine wichtige Rolle, da in diesem Umfeld verstärkt Artefakte auftreten können. Abgesehen von der erhöhten aufgaben-bezogenen Müdigkeit im Simulator (Philip et al., 2005), konnten die Versuchsergebnisse aus Studie 1 erfolgreich im Fahrzeug (Studie 2) repliziert werden.

Erfolgsversprechende Ergebnisse aus Laborversuchen zur Gamma-Aktivität (Fell et al., 2003; Jensen et al. 2007; Landau et al., 2007) konnten im Fahrzeug hingegen nicht bestätigt werden. Die hohe Anzahl an Artefakten und die Komplexität der Fahraufgabe erlauben mit der beschriebenen Messmethode keine zuverlässigen Angaben über die tatsächliche neuronale Aktivität im Gamma Band. Valide Aussagen über die Gamma-Aktivität können nur getroffen werden, wenn sichergestellt werden kann, dass vorhandene Muskelbewegungen und auch andere Artefakte sauber identifiziert und bei der Auswertung sauber von neuronalen Mustern getrennt werden können. Dies war in Studie 1 nicht der Fall. Für die Fahraufgabe mit auditorischer Nebenaufgabe konnte für Elektroden über dem temporalen Kortex (T7, T8, TP9, TP10), die speziell Muskelaktivität des Musculus auricularis superior (oberer Ohrmuskel) und des Musculus sternocleidomastoideus (großer Kopfwender) beinhalten, eine signifikant geringere Gamma-Aktivität gezeigt werden. Bedingt durch die höhere Anzahl an zu verarbeitenden Reizen wurde im Vergleich zur Fahraufgabe ohne Nebenaufgabe aber eine signifikant höhere Gamma-Aktivität erwartet. Dieser Befund spricht eher für eine verringerte Muskelaktivität und ein generell ruhigeres Fahrverhalten, während Aufmerksamkeit auf ein Hörbuch gerichtet war, und lässt nicht den Schluss zu, dass sich die kortikale Gamma-Aktivität mit der Aufgabe verändert. Für die in dieser Studie behandelten Fragestellungen konnten demnach die Hypothesen zur Gamma-Aktivität nicht erfolgreich untersucht werden.

Betrachtet man die Auswirkungen der auditorischen Nebenaufgabe auf die Bremsreaktionszeiten, so zeigt sich eine aufgaben-bedingte Verzögerung um 75 ms. Während die ProbandInnen bei der Fahraufgabe ohne auditorischer Nebenaufgabe im Mittel 728 ms nach Aufleuchten des Bremslichtes des vorausfahrenden Fahrzeugs das Bremspedal berührten, so erfolgte diese Reaktion während des Fahrens mit auditorischer Nebenaufgabe erst nach 803 ms. Sowohl Makishita et al. (2008), als auch Strayer et al. (2006) beobachteten mit einer Median-Reaktionszeit von 760 ms, bzw. einer gemittelten Reaktionszeit von 777 ms ähnliche Ergebnisse während des Fahrens ohne Nebenaufgabe. Strayer et al. (2006) konnten eine Verlängerung der Bremsreaktionszeiten durch den Einfluss eines Telefonats mit Freisprecheinrichtung um durchschnittlich 72 ms zeigen.

Auch Burkhardt (1985) erhielt mit der Dauer von 640 ms ab Beginn der Fixation eines Objekts bis zur Pedalberührung ein ähnliches Ergebnis für Bremsreaktionszeiten. Die Dauer des Teilabschnittes bis zur Fixation des Objekts konnte in Studie 3 der vorliegenden Arbeit nicht ermittelt werden. Man kann aber diese Teilzeit, bedingt durch das Design, in dem die ProbandInnen instruiert waren die Bremslichter des vorausfahrenden Fahrzeuges zu fixieren und schnellstmöglich zu reagieren, als gering annehmen. Dafür spricht auch eine gemittelte, aus dem EMG extrahierte, Reaktionszeit von 337 ms, die die ProbandInnen brauchten um den linken Fuß nach Aufleuchten des Bremslichtes vom Gaspedal zu nehmen. Auch hier konnte bereits eine Verlangsamung der Reaktionen von 64 ms zwischen einer Fahrt ohne (305 ms) und mit auditorischer Nebenaufgabe (369 ms) gefunden werden. Die Verlangsamung der Reaktionszeiten fand daher zu einem Großteil vom Zeitpunkt des Aufleuchtens des Bremslichtes bis zur Muskelreaktion statt. Basierend auf der veränderten Alpha-Aktivität im EEG und der verzögerten Muskelbewegung aus dem EMG kann davon ausgegangen werden, dass eine erhöhte kognitive Beanspruchung durch die auditorische Nebenaufgabe der Grund für die verlängerten Bremsreaktionszeiten ist.

In Studie 3 wurden die für die Fahrerzustandserkennung extrahierten Alpha-Spindelparameter in einer Einzelfall-Klassifikation eingesetzt. Dieser Ansatz ermöglicht eine Vorhersage der mentalen Fahrerzustände für einzelne Probanden über ein 3-Minuten-Fenster. Für die Klassifikation wurden alle vier Parameter (Rate, Dauer, Frequenz, Amplitude) über die Mittelwerte der beiden Bedingungen Fahrt mit und ohne auditorischer Nebenaufgabe mit einbezogen. Für die Unterscheidung konnte in den einzelnen 3-Minuten-Blöcken eine Klassifikation mit 8% Median-Fehler erreicht werden. Es zeigte sich allerdings eine hohe Varianz zwischen den ProbandInnen. Während die Klassifikation für vier ProbandInnen Werte Nahe der Ratewahrscheinlichkeit von 50% ergab, zeigte der Ansatz eine gute Klassifikation (90% korrekte Klassifikation) für elf von 20 ProbandInnen. In einer vorangegangenen Studie von Kohlmorgen et al. (2007) wurde über ähnlich hohe interindividuelle Varianz bei einer Klassifikation auf die Leistung im Alpha-Band berichtet. Für Zeitfenster von 10 Sekunden erzielte der Ansatz für acht von 17 ProbandInnen eine Klassifikationsrate von 70% für die Detektion einer auditorischen Aufgabe. In der vorliegenden Studie wurde bewusst ein breiteres Zeitfenster von drei Minuten gewählt, um eine zuverlässigere Klassifikation des Fahrerzustandes in Bezug auf eine durch eine auditorische Nebenaufgabe beeinflusste Aufmerksamkeit zu ermöglichen. Dadurch könnten unaufmerksame Fahrer im Straßenverkehr besser unterstützt werden. Aktuell greift je nach System ein Bremsassistent erst dann aktiv in die Längs- und Querregelung ein, wenn ein Unfall bereits als unvermeidbar gilt, oder der Bremsassistent unterstützt den Fahrer bei willentlichem Eingreifen, in dem bei zu zögerlichem Bremsen die volle Bremskraft aktiviert wird. Hintergrund dieser Regelung ist, dass der Fahrer verantwortlich für das Führen eines Fahrzeugs ist und erst „bevormundet“ werden darf, wenn zu 100% sichergestellt ist, dass der Fahrer den Unfall nicht mehr vermeiden kann. Diese Schwelle könnte man bei Klassifikation eines unaufmerksamen Fahrers um 75 ms, also die Differenz der Reaktionszeit eines unaufmerksamen Fahrers (~800 ms) und der eines aufmerksamen Fahrers (~725 ms), nach vorne verschieben, um Konsequenzen eines Unfalls noch besser abschwächen zu können oder diesen sogar zu vermeiden.

In dieser Arbeit konnte erfolgreich gezeigt werden, dass Alpha-Spindeln Zustände der Unaufmerksamkeit des Fahrers beschreiben können und im Vergleich zu traditionellen Maßen aus dem Alpha- oder dem Gamma-Band aufgrund besserer Artefakt-Robustheit höhere Effektstärken aufweisen. Die bereits im Simulatorversuch gewonnenen Ergebnisse konnten im Realfeldversuch repliziert werden und der Zusammenhang zu Bremsreaktionszeiten konnte hergestellt werden. Eine Anwendung des EEGs im täglichen Verkehrsgeschehen ist mit dem momentanen Stand der Technik noch nicht denkbar. Bei der Weiterentwicklung von Fahrerassistenzsystemen kann es aber als wertvolles Außenkriterium herangezogen werden. Die Klassifikation über dreiminütige Zeitfenster ermöglicht eine valide Detektion unaufmerksamer Fahrerzustände und das EEG liefert dabei Zusatzinformationen über die Internalisierung der Aufmerksamkeit des Fahrers, die mit Fahrerbeobachtungskameras nicht gemessen werden kann.

4 Literaturliste

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

Bollimunta, A., Mo, J., Schroeder, C. E., & Ding, M. (2011). Neuronal Mechanisms and Attentional Modulation of Corticothalamic Alpha Oscillations. *The Journal of Neuroscience, 31*(13), 4935–4943.

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

Broadbent, D. E. (1958). *Perception and communication*. Oxford: Pergamon Press.

Brookhuis, K. A., & Waard, D. de (2010). Monitoring drivers' mental workload in driving simulators using physiological measures: Assessing Safety with Driving Simulators. *Accident Analysis & Prevention, 42*(3), 898–903.

Burkhardt, M. (1985). *Reaktionszeiten bei Notbremsvorgängen*. Verlag TÜV Rheinland.

CARE road accidents database (2009). *Road safety evolution in EU*. Retrieved from http://ec.europa.eu/transport/road_safety/pdf/observatory/historical_evol.pdf.

Cohen, R. A. (1993). *The neuropsychology of attention*. *Critical issues in neuropsychology*. New York: Plenum Press.

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

Fell, J., Fernández, G., Klaver, P., Elger, C. E., & Fries, P. (2003). Is synchronized neuronal gamma activity relevant for selective attention? *Brain Research Reviews, 42*(3), 265–272.

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

Gratzer, W. (2009). Informationsaufnahme beim Kraftfahrer. In H. Burg & A. Moser (Eds.), *Handbuch Verkehrsunfallrekonstruktion. Unfallaufnahme, Fahrdynamik, Simulation. 2., aktualisierte Auflage.* Vieweg+Teubner Verlag / GWV Fachverlage GmbH, Wiesbaden.

Gruber, T., Müller, M. M., Keil, A., & Elbert, T. (1999). Selective visual-spatial attention alters induced gamma band responses in the human EEG. *Clinical Neurophysiology, 110*(12)*,* 2074–2085.

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

Horrey, W. J., & Wickens, C. D. (2006). Examining the Impact of Cell Phone Conversations on Driving Using Meta-Analytic Techniques. *Hum. Factors, Vol. 48(No. 1),* 196–205.

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

James, W. (1890). *The Principles of Psychology* (Vol. 1). New York: Henry Holt.

Jensen, O., Kaiser, J., & Lachaux, J.-P. (2007). Human gamma-frequency oscillations associated with attention and memory: July INMED/TINS special issue--Physiogenic and pathogenic oscillations: the beauty and the beast. *Trends in Neurosciences, 30*(7)*,* 317–324.

Jokisch, D., & Jensen, O. (2007). Modulation of Gamma and Alpha Activity during a Working Memory Task Engaging the Dorsal or Ventral Stream. *J. Neurosci., 27*(12)*,* 3244–3251.

Kahnemann (1973). *Attention and Effort*. Englewood Cliffs, NJ: Prentice Hall.

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

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

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews, 53*(1)*,* 63–88.

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

Landau, A. N., Esterman, M., Robertson, L. C., Bentin, S., & Prinzmetal, W. (2007). Different Effects of Voluntary and Involuntary Attention on EEG Activity in the Gamma Band. *J. Neurosci., 27*(44)*,* 11986–11990.

Makishita, H., & Matsunaga, K. (2008). Differences of drivers' reaction times according to age and mental workload. *Accident Analysis & Prevention, 40*(2), 567–575.

Müller, M. M., Gruber, T., & Keil, A. (2000). Modulation of induced gamma band activity in the human EEG by attention and visual information processing. *International Journal of Psychophysiology, 38*(3)*,* 283–299.

NHTSA (2010). *Distracted Driving 2009* (DOT HS 811 379). Washington, DC: National Highway Traffic Safety Administration.

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

Papadelis, C., Chen, Z., Kourtidou-Papadeli, C., Bamidis, P. D., Chouvarda, I., Bekiaris, E., & Maglaveras, N. (2007). Monitoring sleepiness with on-board electrophysiological recordings for preventing sleep-deprived traffic accidents. *Clinical Neurophysiology, 118*(9)*,* 1906–1922.

Pfurtscheller, G. (2003). Induced Oscillations in the Alpha Band: Functional Meaning. *Epilepsia, 44,* 2–8.

Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., Charles, A., & Bloulac, B. (2005). Fatigue, Sleepiness and Performance in Simulated Versus Real Driving Conditions. *Sleep, 28*(12).

Posner, M. I., & Rafal, R. D. (1987) Cognitive Theories of Attention and the Rehabilitation of attentional deficits. In M. J. Meier, A. L. Benton, & L. Diller (Eds.), *Neuropsychological Rehabilitation* (pp. 182–201). Edinburgh: Churchill Livingstone.

Ray, W. J., & Cole, H. W. (1985). EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science, 228*(4700), 750–752.

Regan, M. A., Hallett, C., & Gordon, C. P. (2011). Driver distraction and driver inattention: Definition, relationship and taxonomy. *Accident Analysis & Prevention, 43*(5), 1771–1781.

Reinoso-Suárez, F., Andrés, I. de, & Garzón, M. (Eds.) (2011). *Advances in Anatomy, Embryology and Cell Biology: Vol. 208. Functional Anatomy of the Sleep-Wakefulness Cycle: Wakefulness*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

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

Schmidt, R. F., Thews, G., & Lang, F. (Eds.) (2000). *Physiologie des Menschen* (28. korrigierte und aktualisierte Auflage). Berlin: Springer.

Shaw, J. C. (2003). *The brain's alpha rhythms and the mind*. New York: Elsevier.

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

Statistisches Bundesamt (2010). *Verkehrsunfälle - Unfallentwicklung im Straßenverkehr 2009*. Wiesbaden.

Statistisches Bundesamt (2012). *Entwicklung der Zahl der im Straßenverkehr Getöteten 1953-2011*. Retrieved from https://www.destatis.de.

Strayer, D. L., Drews, F. A., & Crouch, D. J. (2006). A comparison of the cell phone driver and the drunk driver. *Hum. Factors, 48*(2), 381–391.

Stutts, J. C., Reinfurt, D. W., Staplin, L., & Rodgman, E. A. (2001). *The role of driver distraction in traffic crashes*. Retrieved from http://www.aaafoundation.org/pdf/distraction.pdf.

van Dijk, H., Schoffelen, J.-M., Oostenveld, R., & Jensen, O. (2008). Prestimulus Oscillatory Activity in the Alpha Band Predicts Visual Discrimination Ability. *The Journal of Neuroscience, 28*(8), 1816–1823.

Waard, D. de (1996). *The Measurement of Drivers' Mental Workload* (Dissertation). Rijksuniversiteit, Groningen.

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

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention*. Orlando: Academic Press.

5 Einzelarbeiten

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Schrauf, M., Sonnleitner, A., Simon, M., & Kincses, W. E. (2011) EEG Alpha Spindles as Indicators for Prolonged Brake Reaction Time During Auditory Secondary Tasks in a Real Road Driving Study. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting September 2011 55(1),* 217-221.

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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

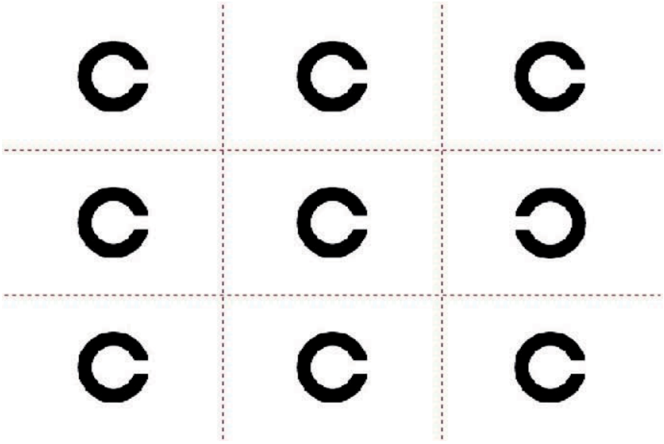

Fig. 1. Visuomotor task: 3 × 3-matrix.

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

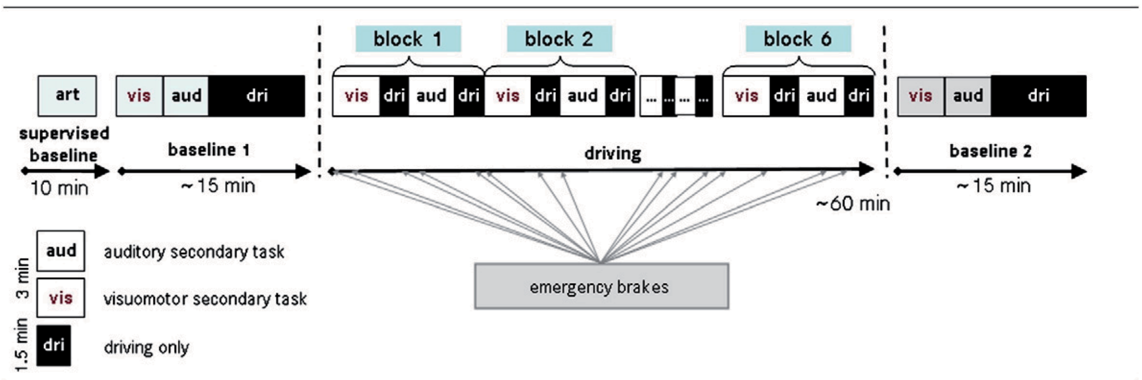

Fig. 2. Test procedure.

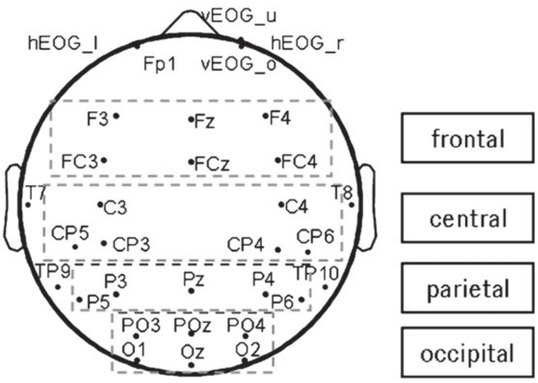

Fig. 3. Regions of interest (a total of 32 electrodes): to investigate the distribution of alpha spindles, the 23 EEG channels were divided into four regions.

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	η²	Type	F	p	η²
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	η²	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.

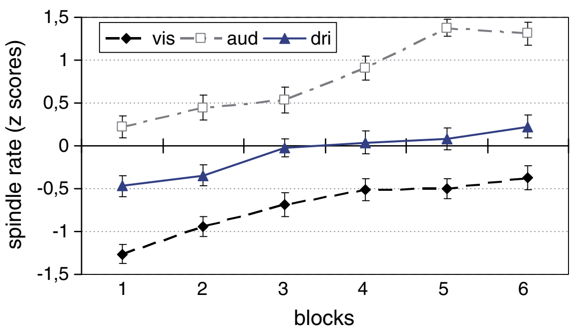

Fig. 4. Alpha spindle rate (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

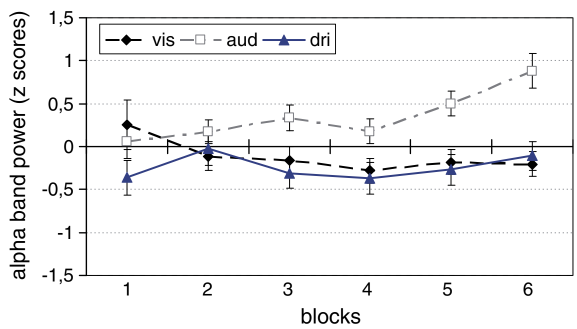

Fig. 6. Alpha band power (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

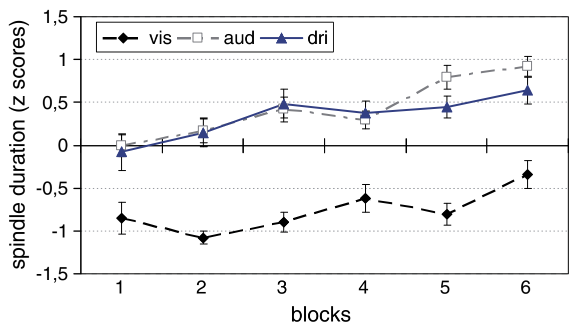

Fig. 5. Alpha spindle duration (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

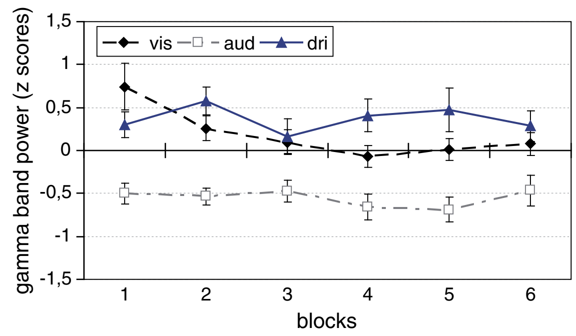

Fig. 7. *Gamma band power* (z-scores) for the variables *time-on-task* (6 blocks) and *distractions* (vis = visuomotor, aud = auditory, dri = driving only condition). Error bars present the standard errors of the means.

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	η^2
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	η^2
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.

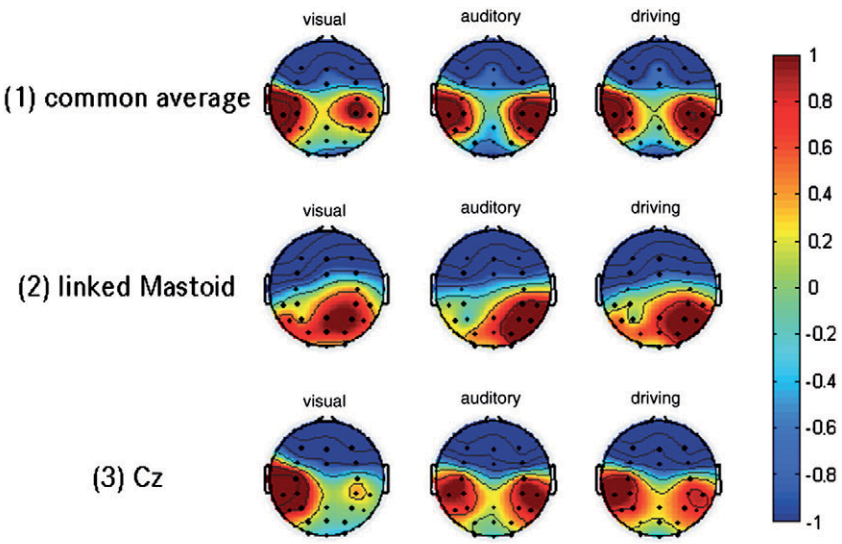

Fig. 8. Distribution of alpha spindles with regards to different references, calculated for each condition separately (values are z-scores of collectively occurred alpha spindles averaged over all participants).

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	η²	Post-hoc effect	p
Stimulus	Reaction time	41.598	<.001	.606	Traffic light > stop sign	<.001
		F(2,54)	p	η²	Post-hoc effect	p
Distraction	Reaction time	5.713	.015	.175	Auditory > driving	.003
		F(2,54)	p	η²	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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References

Berger, H., 1929. Über das Elektroenzephalogramm des Menschen I. Archives of Psychiatrie, pp. 527–570.

Birbaumer, N., Schmidt, R.F. (Eds.), 2006. *Springer-Lehrbuch. Biologische Psychologie* (6., vollst. überarb. und erg. Aufl.). Springer Medizin, Heidelberg.

Bollimunta, A., Mo, J., Schroeder, C.E., Ding, M., 2011. Neuronal mechanisms and attentional modulation of corticothalamic alpha oscillations. The Journal of Neuroscience 31 (13), 4935–4943.

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

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

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

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

Fell, J., Fernández, G., Klaver, P., Elger, C.E., Fries, P., 2003. Is synchronized neuronal gamma activity relevant for selective attention? Brain Research Reviews 42 (3), 265–272.

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

Gruber, T., Müller, M.M., Keil, A., Elbert, T., 1999. Selective visual-spatial attention alters induced gamma band responses in the human EEG. Clinical Neurophysiology 110 (12), 2074–2085.

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

Jensen, O., Kaiser, J., Lachaux, J.-P., 2007. Human gamma-frequency oscillations associated with attention and memory: July INMED/TINS special issue–Physiogenic and pathogenic oscillations: the beauty and the beast. Trends in Neurosciences 30 (7), 317–324.

Jokisch, D., Jensen, O., 2007. Modulation of gamma and alpha activity during a working memory task engaging the dorsal or ventral stream. Journal of Neuroscience 27 (12), 3244–3251.

Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Research Reviews 29 (2–3), 169–195.

Klimesch, W., Sauseng, P., Hanslmayr, S., 2007. EEG alpha oscillations: the inhibition-timing hypothesis. Brain Research Reviews 53 (1), 63–88.

Landau, A.N., Esterman, M., Robertson, L.C., Bentin, S., Prinzmetal, W., 2007. Different effects of voluntary and involuntary attention on EEG activity in the gamma band. Journal of Neuroscience 27 (44), 11986–11990.

Lutzenberger, W., Preissl, H., Birbaumer, N., Pulvermüller, F., 1997. High-frequency cortical responses: do they not exist if they are small? Electroencephalography and Clinical Neurophysiology 102 (1), 64–66.

Mann, C.A., Sterman, M.B., Kaiser, D.A., 1996. Suppression of EEG rhythmic frequencies during somato-motor and visuo-motor behavior. International Journal of Psychophysiology 23 (1–2), 1–7.

Müller, M.M., Gruber, T., Keil, A., 2000. Modulation of induced gamma band activity in the human EEG by attention and visual information processing. International Journal of Psychophysiology 38 (3), 283–299.

Nunez, P.L., 1981. Electric Fields of the Brain: The Neurophysics of EEG. Oxford University Press, New York.

Pereda, E., Gamundi, A., Rial, R., González, J., 1998. Non-linear behaviour of human EEG: fractal exponent versus correlation dimension in awake and sleep stages. Neuroscience Letters 250 (2), 91–94 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9697926.

Pfurtscheller, G., 2003. Induced oscillations in the alpha band: functional meaning. Epilepsia 44, 2–8.
Pfurtscheller, G., Lopes da Silva, F.H., 1999. Event-related EEG/MEG synchronization and desynchronization: basic principles. Clinical Neurophysiology 110 (11), 1842–1857.
Pfurtscheller, G., Stancák, A., Neuper, C., 1996. Event-related synchronization (ERS) in the alpha band – an electrophysiological correlate of cortical idling: a review: new advances in EEG and cognition. International Journal of Psychophysiology 24 (1–2), 39–46.
Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., Charles, A., Bloulac, B., 2005. Fatigue, sleepiness and performance in simulated versus real driving conditions. Sleep 28 (12).
Ray, W.J., Cole, H.W., 1985. EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. Science 228 (4700), 750–752.
Reinoso-Suárez, F., de Andrés, I., Garzón, M. (Eds.), 2011. *Advances in Anatomy, Embryology and Cell Biology: Vol. 208. Functional Anatomy of the Sleep-Wakefulness Cycle: Wakefulness*. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.
Schlögl, A., 2000. The Electroencephalogram and the adaptive Autoregressive Model: Theory and Applications. Shaker Verlag, Aachen.
Schmidt, R.F., Thews, G., Lang, F. (Eds.), 2000. Physiologie des Menschen, 28. korrigierte und aktualisierte Auflage. Springer, Berlin.
Schmidt, E.A., Schrauf, M., Simon, M., Fritzsche, M., Buchner, A., Kincses, W.E., 2009. Drivers' misjudgement of vigilance state during prolonged monotonous daytime driving. Accident Analysis and Prevention 41 (5), 1087–1093.
Shaw, J.C., 2003. The Brain's Alpha Rhythms and the Mind. Elsevier, New York.
Sherman, S.M., 2001. Tonic and burst firing: dual modes of thalamocortical relay. Trends in Neurosciences 24 (2), 122–126.
Simon, M., Schmidt, E.A., Kincses, W.E., Fritzsche, M., Bruns, A., Aufmuth, C., Bogdan, M., Rosenstiel, W., Schrauf, M., 2011. EEG-Alpha spindle measures as indicators of driver fatigue under real traffic conditions. Clinical Neurophysiology 122, 1168–1178.
Staughton, G.C., Storie, V.J., 1977. Methodology of an in-depth accident investigation (Survey Report No. 672). Crowthorne, Berks.

ASSESSING DRIVER STATE –

Neurophysiological Correlates of Attentional Shift During Real Road Driving

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ABSTRACT

In order to investigate ecologically robust parameters in the EEG as correlates of driver attentional shift, we conducted a real road driving study with *N*=40 participants which performed two different secondary tasks (i.e. visuomotor and auditory). Due to safety considerations, adaptive cruise control was activated all the time and participants were not allowed to overtake. The visuomotor task consisted of a Landolt-rings task presented on an extra display. In the auditory task, the participants were instructed to detect predefined words during the presentation of an audio book and had to answer a question with regard to the content at the end of every chapter.

In the EEG, alpha spindles show a significantly higher occurrence rate during the auditory secondary task and a significantly lower rate during the visuomotor secondary task as compared to driving only. For alpha spindle duration significantly shorter alpha spindles during the visuomotor secondary task as compared to the auditory secondary task and to driving only could be found.

Effects on alpha spindle rate and duration while performing secondary tasks on top of the driving task result from attentional shift according to the task modality. The results are consistent with the assumption that alpha spindles indicate active inhibition of visual information processing. As compared to alpha band power, the measures of alpha spindle rate and alpha spindle duration were less prone to artifacts and the effects were more pronounced, which

allows for a more accurate classification of different attentiveness levels while driving in real traffic.

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Short version of title:
Neurophysiological correlates of attentional shift during real road driving

Keywords:
Alpha spindles; alpha rhythm; real road driving; EEG; driver monitoring; distraction; secondary task; visuomotor; auditory

Précis:
A real road driving study with two different secondary tasks was conducted. Alpha spindle rate in the EEG is significantly higher during an auditory secondary task and significantly lower during a visuomotor secondary task as compared to driving only.

INTRODUCTION

Although the number of traffic deaths decreased over the past years, in 2009 still 34.500 people died in road accidents in the European Union (CARE, European road accident database, 2010), thereof 4.152 on German roads, 68% being caused by human error (Statistisches Bundesamt, 2010). The National Highway Traffic Safety Administration (NHTSA) estimates at least 25% of police-reported crashes as a matter of driver inattention (Stutts et al., 2001), caused by a variety of distractions such as using a telephone, handling the navigation system, drinking or eating. Dingus et al. (2006) broadly widened the definition and combined four categories of inattention (secondary task, drowsiness, inattention to forward roadway and nonspecific eye glance). Using numbers of crashes and near-crashes of a 100-Car Study database, they found 78% of crashes and 65% of near-crashes to be related to driver inattention. Secondary tasks (i.e. wireless devices, internal- or external distractions) had the highest impact.

In order to find neurophysiological descriptors of driver's attentional shift we conducted a real road driving study with sections of controlled distraction during the driving task to describe different driver states. With this information it would be possible to improve the development of driver assistance systems. In the EEG, critical driver states, i.e. inattentiveness, can be detected and used as a reference in order to discriminate the same critical states based on driving behavior data. Hence, algorithms can be trained to enable the detection of such states in commercially available vehicles.

Attention

In the past, the psychological concept of "attention" was subject of extensive and controversy research. For example, Broadbent (1958) assumed in his filter theory that only one source of information reaches the stage of deeper information processing. In contrast, Deutsch & Deutsch (1963) recommended that the attentional bottleneck occurs at a later stage of information processing. Stimuli being perceptually processed regardless of whether they are attended to or not, without accessing consciousness. This would indicate that there are no changes in brain activity during early stages of information processing regardless of an aware or unattended driver state. Kahnemann (1973) proposed a central processing unit in his model of divided attention where resources of attention are finite and are allocated to different tasks requiring various cognitive capacities. Wickens (1984) also used a capacity model to describe the actual amount of resources available for a task. In his multiple-resources-model he proposed that different resources may be associated with different input modalities (e.g. visual or auditory), different stages of processing (encoding, central processing, or responding), two types of encoding (spatial vs. verbal) and two types of response (manual vs. vocal) without interfering each other. Therefore, simultaneous information processing of a visuomotor task and a verbal auditory task should not interfere as much as information processing within one modality.

Posner & Rafal (1987) subdivided the term attention into "focused attention", "divided attention" and "vigilance". They distinguished between a tonic (e.g. dependent of circadian rhythm) and a phasic activation (e.g. short-termed and stimulus-based). Driving a car, while listening to the radio or talking, is an example of divided attention depending on task demands and the type of information to be processed.

Since driving is a complex multimodal task, secondary tasks have a high influence on visual information processing of the driving task accompanied with an increased risk of accidents.

Neurophysiological measurements

Recently, different methods were used to describe neuronal processes underlying attention shifts during driving. Bowyer et al. (2009) investigated the influence of conversation while viewing a driving scene using MEG. During the primary task, higher brain activity in the visual cortex (85 ms after stimulus onset) and in the right superior parietal lobe (200-300 ms after stimulus onset) led to shortened reaction time to small red lights presented to the left or below a driving scene. Additional hands-free conversation reduced the amplitude of these effects and increased mean reaction time with no statistically significant difference in miss rates. In a companion paper, Hsieh et al. (2009) investigated a frontal-parietal network that indicates effects of conversation on visual event detection. Reaction times to visual events in an fMRI setting were prolonged during covert conversation as compared to the driving-only condition. They assume a top-down influence of frontal regions on the synchronization of neural processes within the two key regions of superior parietal lobe and extrastriate visual cortex.

Next to stationary measurements like MEG or fMRI with a high spatial and temporal resolution, parameters in the EEG have proved to be appropriate indicators for detecting different driver states in simulators and also during real road driving (Papadelis, 2007; Schmidt et al., 2009; Brookhuis & de Waard, 2010). Especially, EEG activity in the alpha band (8-12 Hz) is associated with inhibited visual information processing during secondary tasks. Several findings give evidence that alpha band oscillations represent active inhibition processes irrespective of the direction of attention (Ray & Cole, 1985) as well as irrespective of the active inhibition of sensory information in task-irrelevant cortical areas (Jokisch & Jensen, 2007; Klimesch et al., 2007). Cooper et al. (2003) found a clear relationship between alpha activity and both direction of attention (external and internal) and increased task demands. Alpha amplitudes were higher during internally directed attention and during increased workload at various scalp sites. Van Dijk et al. (2008) compared prestimulus brain activity in the MEG for a visual discrimination task. They suggested that alpha band power serves to modulate visual information processing and an increase in prestimulus alpha band power goes along with decreased visual discrimination ability.

Foxe et al. (1998) found similar effects in parieto-occipital activity (~10 Hz). Participants had to perform an intermodal selective attention paradigm in which word cues were visually presented. Participants showed a higher parieto-occipital activity in preparation for anticipated auditory input as compared to visual input which reflects a disengaged visual attentional system.

An even more promising parameter seems to be the extraction of alpha spindles out of the spontaneous EEG.

Alpha spindles

Alpha-spindles are short narrow-band bursts in the alpha band, which can be visually observed in spontaneous EEG data especially in subjects having their eyes closed. Simon et al. (2011) reported a method based on time-frequency decomposition to automatically detect and characterize alpha spindles with regard to their duration, amplitude and frequency. The typical “waxing and waning” (Shaw, 2003) of the alpha rhythm can be described by means of burst-like alpha spindle activity. Counting the occurrence of alpha spindles over one minute leads to the so-called *alpha spindle rate*.

Beside the fatigue-related long-term effect on the alpha spindle rate (Simon et al., 2011) there are also short-term variations indicating additional influences of phasic cognitive processes.

Alpha spindles are assumed to be controlled by the interaction between thalamic relay cells and the thalamic reticular nucleus. 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). It is assumed that the thalamus plays an important role in adjusting attention by projecting arousal from reticular activation to cortical processing systems (Cohen, 1993). In addition, the thalamus and the cerebral cortex are widely and complexly interconnected anatomically, phylogenetically and functionally (Reinoso-Suarez, 2010). 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 (Birbaumer & Schmidt, 2006). Selective attention makes use of these mechanisms by weighting 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.

Hypothesis

We describe three different driver states, i.e. driving with visuomotor distraction, driving with auditory distraction, and driving without distraction. *Alpha spindle rate* is expected (a) to increase while performing an auditory secondary task indicating decreased visual information processing and (b) to decrease while performing a visuomotor secondary task indicating increased visual information processing in comparison to driving without distraction respectively. These assumptions are based on the inhibition-timing hypothesis (Klimesch et al., 2007).

Methods

Participants

A total of 46 subjects participated in this study (22-58 years, mean: 35 years), 34 male and 12 female. Subjects were recruited from an in-house database, in which voluntary participants were listed for driving experiments. As a prerequisite all participants had a special training on our test vehicles, which is necessary for driving special equipped cars on public roads.

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, there was no monetary compensation. Informed consent was obtained after the task had been explained. Participants were told to be responsible for limit exceedances. All experimental procedures were conducted in accordance with the Declaration of Helsinki. Subjects were able to abort the experiment at any time, without encountering any penalties.

Due to technical problems six datasets had to be excluded from further analysis; in total 40 datasets entered the analysis.

Vehicles

Three identically equipped test cars (two Mercedes Benz S-Class, one Mercedes-Benz E-Class) were used in the study. Due to safety reasons the cars had an additional brake- and gas-pedal in the passenger footwell area. Investigators underwent a safety training to be able to identify critical situations in time and intervene by operating from the passenger seat.

Physiological recordings

After agreeing to the study participants were fitted with a 16-electrode-cap (ActiCap, Brain Products GmbH). A set of eleven electrodes was positioned according to the international 10-20 system. Four facial electrodes measured horizontal and vertical eye movements and were positioned about 2 cm above and below the right eye and at the left and right outer canthi.

Each pair of vertical and horizontal electrodes was referenced bipolar. EEG was recorded relative to Cz, all impedances were maintained less than 10 kΩ. Data were digitized at 250 Hz with a bandpass-filter (low: 0,531 Hz, high: 100 Hz) and a 50 Hz notch filter was applied to remove power line interference.

Test procedure

Before starting the drive, participants performed a supervised baseline (see also **Figure 1**), in which ocular artifacts (blinks, saccades) and muscle artifacts (head movements, chewing, pushing the brake pedal) were recorded. The supervised baseline was followed by a familiarization period, in which the visuomotor and the auditory secondary task were performed for one minute each without driving. The secondary tasks will be explained in the following sections. Subsequently, participants drove about 2 km until they entered the highway A81, on which they drove 128 km to the south until "Kreuz Singen" in order to get accustomed to the vehicle and the adaptive cruise control function (baseline driving).

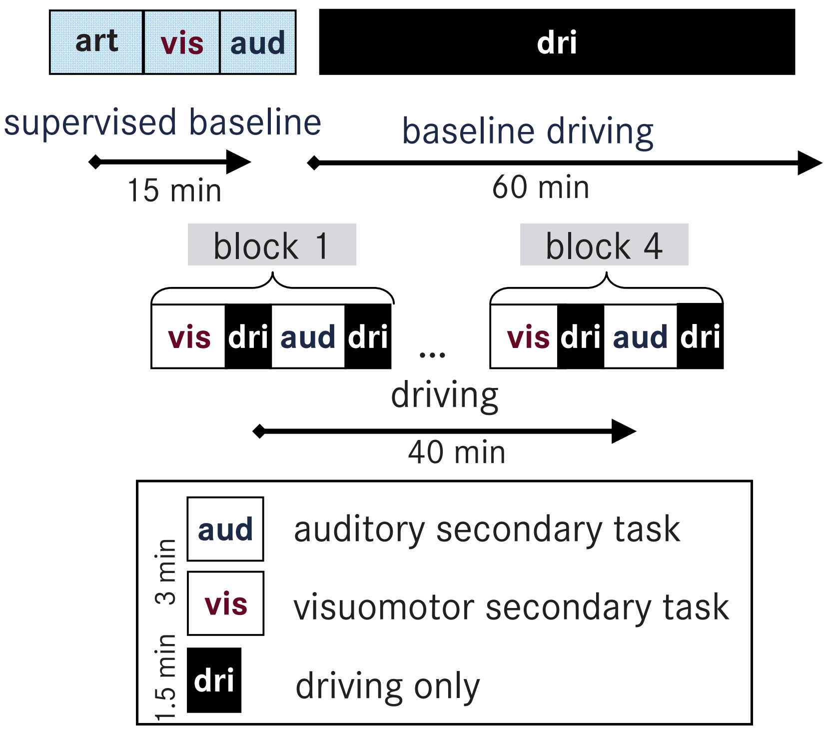

Figure 1: Test procedure

Participants were instructed to always prioritize the primary task (driving) and to drive in accordance to official traffic regulations. The maximum speed allowed was 140 km/h (~87 mph). Participants were instructed to activate the adaptive cruise control function at 140 km/h and they were not allowed to overtake during the task. The main study consisted of four blocks and started at exit "Kreuz Singen", where they were instructed to return back to exit "Böblingen/Sindelfingen", which corresponds to a total distance of 260 km. Between the blocks there were short breaks in which participants could give a short feedback and they were allowed to overtake if necessary. Each block consisted of three minutes driving while performing the visuomotor secondary task, 1.5 minutes of driving without additional secondary task, three minutes of driving with the auditory secondary task and again 1.5 minutes of driving without secondary task. The beginning and the end of every task was denoted automatically by recorded announcements. Data collected between blocks and during announcements were excluded from further analysis. The entire experiment lasted about two hours.

Visuomotor secondary task

During the visuomotor task (Visual Task v2.20, developed by Daimler AG, 2008) a 2x2-matrix of four Landolt rings was presented on a separate 18-inch LCD-TFT display. The display was located at the central console on the right side of the navigation system. The 2x2 matrix contained three identical rings and one distractor with the opening at a different position **(Figure 2).** Participants had to determine if the distractor was positioned on the left or the right side of the screen by pushing the corresponding button on an external number keypad (4 – left side, 6 – right side). This keypad was positioned within driver's reach on the lower central console. After pushing a button the next matrix appeared immediately. This secondary task lasted for three minutes. The number of correctly identified distractors served as performance measure.

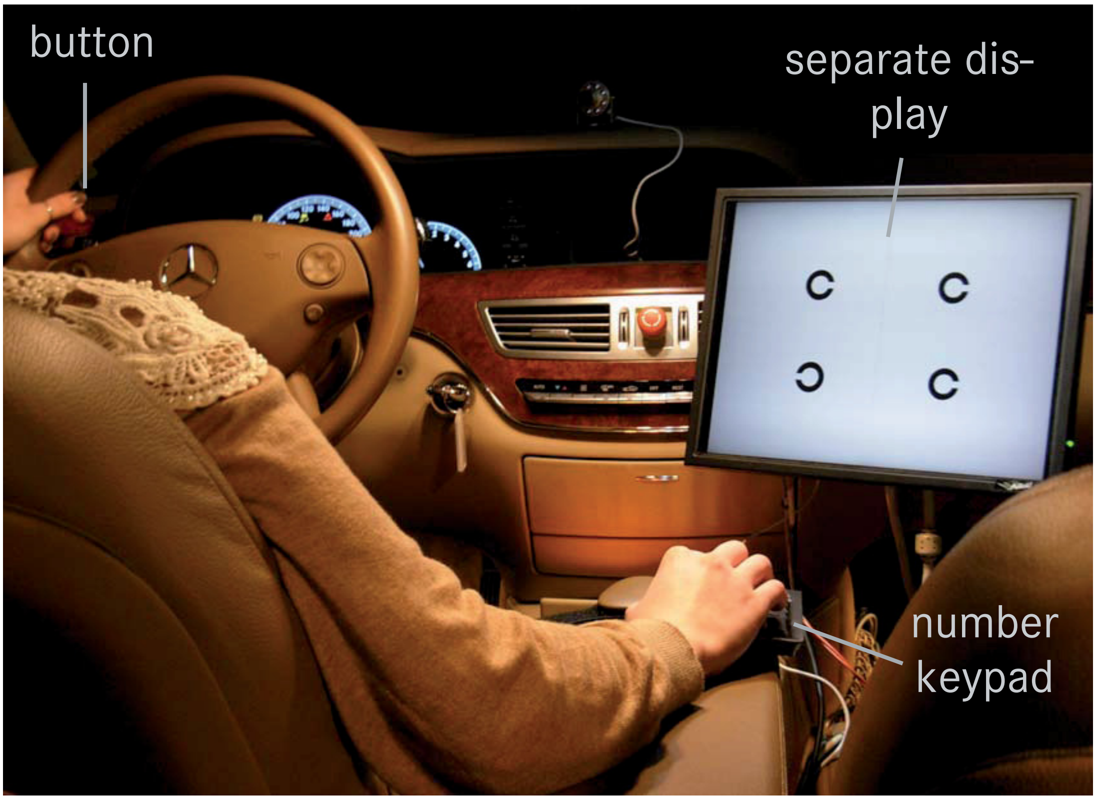

Figure 2: Experimental setup

Auditory secondary task

Participants listened to parts of an audio book recording of a travelogue ("Sieben Jahre in Tibet" [Seven Years in Tibet], Harrer, 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 (see **Figure 2**). In every chapter the target word "die" appeared between 17 and 19 times. The number of detected target words served as performance measure. At the end of each three-minute block participants were instructed to answer a question about the content of the previously presented section of the audio book by choosing the correct answer out of three possible alternatives. The purpose of this combination of continuous detection task and a following question was to maximize the probability of participants directing their attention to the audio book, while engaging their working memory. This auditory secondary task is designed in accordance to listening to a telephone call.

Data analysis

EEG-data (11 channels) were corrected on-line from eye-blink artifacts.

The supervised baseline was used to estimate the influence of vertical and horizontal eye movements on each EEG channel separately by applying a regression analysis. After determining regression coefficients in the baseline, EOG activity can be subtracted from each EEG channel online during the actual drive. This method is similar to the described algorithms of Gratton & Coles (1983) and Schlögl et al. (2007).

Alpha spindles were detected on-line using an algorithm implemented in accordance to Simon et al. (2011). In this method, EEG data is divided into segments of 1 s duration and 750 ms overlap. After subtracting the segment mean of the according channel, each segment is multiplied by a Hamming window. An FFT is computed for the segments and it is checked whether the spectral maximum between 3 to 40 Hz lies within the predefined 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) to model the typical 1/f-like EEG spectrum (Pereda et al., 1998). Scaling this curve with the ratio of the current segment power to the mean signal power of all segments leads to an adaptation to the current noise power. 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 counted as one single 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, the occurrence rate of spindles (alpha spindle rate) can be computed in a moving average window of one to several minutes.

In this study, two different parameters of the alpha spindles (*alpha spindle rate, alpha spindle duration*) were analyzed and averaged over all cortical EEG electrode sites.

In order to minimize false detected spindles during muscular or technical artifacts, an artifact detection method with an auto-regression based approach, similar to the method described by Schlögl (2000), was applied. Following a conservative approach, only data segments that carry a temporal and spatial pattern, resembling that of neural sources were accepted, whereas detected alpha spindles during an artifact were excluded from further analysis. Statistical analysis was performed using MATLAB (R2009b) and PASW Statistics 18.

Experimental design

There were two independent variables, *time-on-task* (four blocks) and *distraction* (visuomotor secondary task, auditory secondary task, driving without secondary task). The dependent variables were EEG measures of attention, i.e. *alpha spindle rate, alpha spindle duration,* and performance measures from the secondary tasks, i.e. correctly identified Landolt ring distractors as well as words in the visuomotor and auditory secondary task, respectively.

An a priori statistical power analysis using G*Power 3.1.2 (Faul et al., 2007) 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 $\varepsilon = .6$ (values were determined in a preceding study), and $\alpha = \beta = .05$, a total sample size of 26 was needed. A post-hoc power analysis showed that given a final sample of $N = 40$, the power $(1 - \beta) = .995$ was adequate.

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 analysis using comparison of main effects by one-step Sidak (Sidak, 1971). For the variable *time-on-task* a post-hoc trend analysis was calculated using polynomial contrasts. Only statistically significant differences and trends are reported.

Results

Sphericity (Mauchly's Test of Sphericity) can not be assumed for the independent variable *time-on-task* with respect to the dependent variable *alpha spindle rate*. In these cases Greenhouse-Geisser corrected values are reported.

Alpha spindles

Table 1 summarizes the results of the ANOVAs for the effects of *time-on-task* and *distraction*. Reported values are means over all cortex areas (11 EEG channels). We found a significant *time-on-task* effect for the variable *alpha spindle rate* **(Figure 3)** as well as for the variable *alpha spindle duration* **(Figure 4)**. Significant linear trends show a monotonous increase in *alpha spindle rate* and *alpha spindle duration*.

For the variable *distraction,* significant differences for all three conditions were found for *alpha spindle rate* and *alpha spindle duration*. Pairwise comparisons showed that *alpha spindle rate* is highest while driving and performing the auditory secondary task followed by driving only and is lowest while performing the visuomotor secondary task. For *alpha spindle duration* we found significant differences between driving with the visuomotor secondary task and driving with the auditory secondary task as well as between driving without secondary task and driving with the visuomotor secondary task. No statistically significant differences could be found between driving with the auditory secondary task and driving only.

Table 1: Statistical results (ANOVA for repeated measures), spindle parameters for the variables *time-on-task* and *distraction* (*N*=40).

		Main effect			Trend analysis (polynomial)			
		F(3,117)	**p**	**η²**	**Type**	**F**	**p**	**η²**
time-on-task	spindle rate	6.494	<.001	.143	Linear	9.216	.004	.191
	spindle duration	3.551	.018	.083	Linear	8.100	.007	.172
		Main effect			**Pairwise Comparison (Sidak)**			
		F(2,78)	**p**	**η²**	**post-hoc effect**			**p**
distraction	spindle rate	144.256	<.001	.787	auditory > visuomotor			<.001
					auditory > driving			<.001
					driving > visuomotor			<.001
	spindle duration	39.357	<.001	.502	auditory > visuomotor			<.001
					driving > visuomotor			<.001

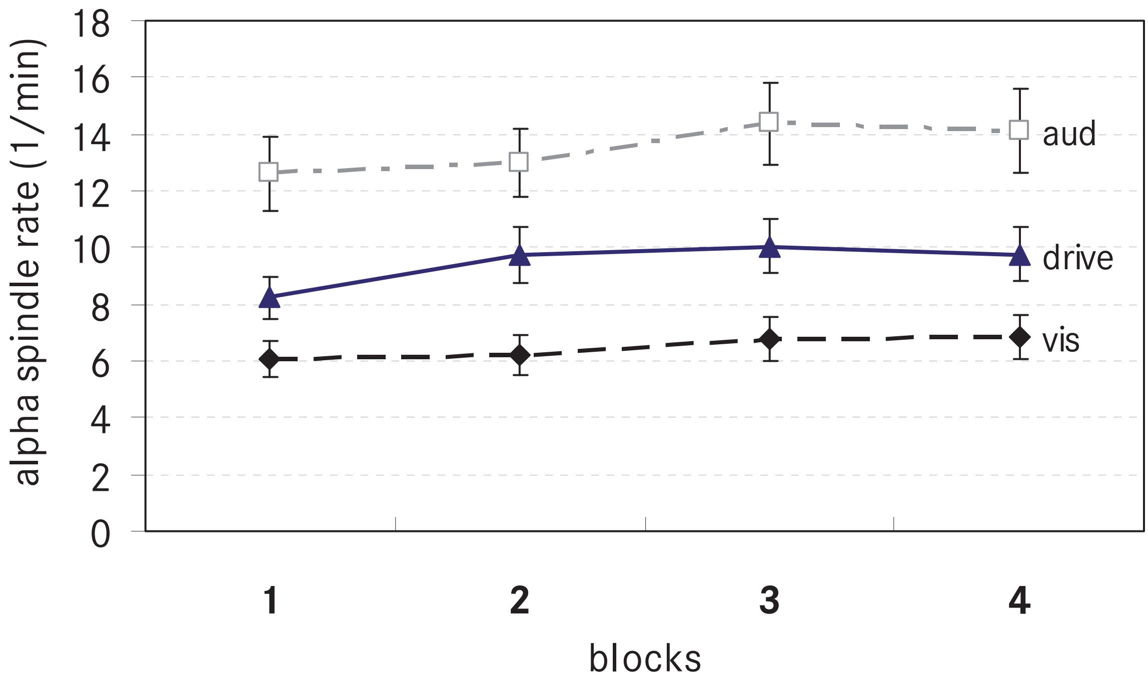

Figure 3: Alpha spindle rate for the variables *time-on-task* (4 blocks) and *distraction* (vis=visuomotor, aud=auditory, drive=driving only condition). Error bars present the standard errors of the means.

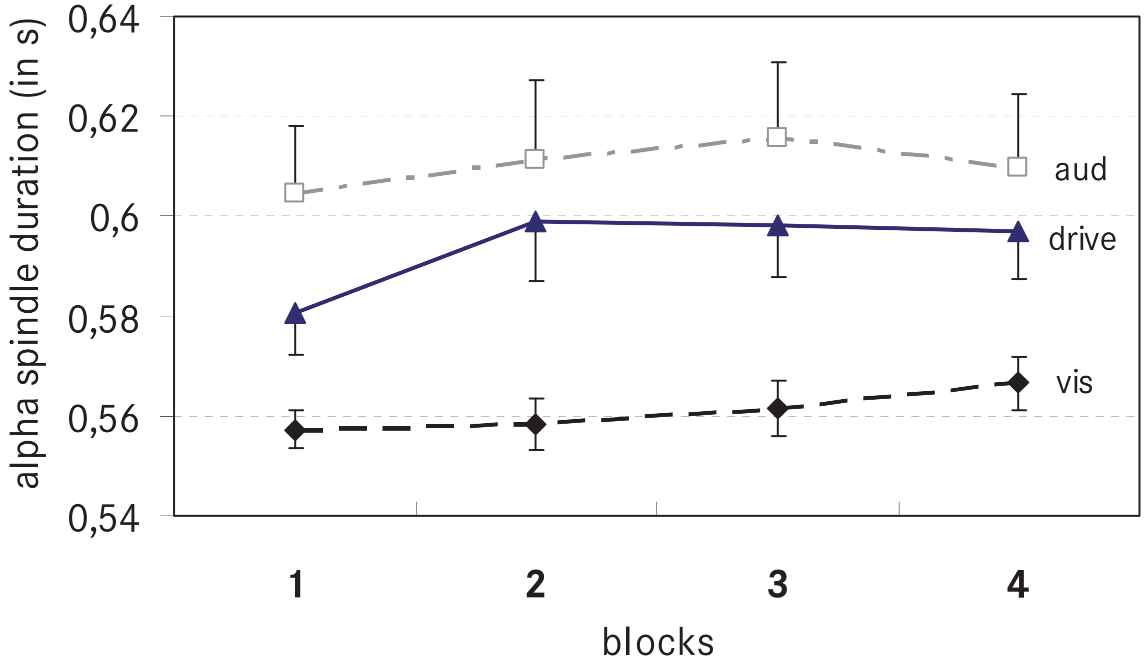

Figure 4: Alpha spindle duration for the variables *time-on-task* (4 blocks) and *distraction* (vis=visuomotor, aud=auditory, drive=driving only condition). Error bars present the standard errors of the means.

Secondary tasks

For the performance in the visuomotor secondary task there was a significant effect for *time-on-task* (ANOVA for repeated measures: $F(2.407,93.860) = 42.434$, $p < .001$, $\eta^2 = .521$). The post-hoc trend analysis showed a linear trend ($p < .001$, $\eta^2 = .666$). Performance in the final block (M = 126.1, SD = 48.1) was significantly higher than in the first of four blocks (M = 82.7, SD = 39.9).

For the auditory secondary task participants found 80% of all predetermined words ("die") in the text, and they correctly answered 90% of all questions. We could not find effects of *time-on-task* for the auditory task.

Discussion

Distraction

The results for the two calculated alpha spindle parameters (rate, duration) suggest reliable and sensitive measures for both kinds of driver distraction and the hypothesis of an increased alpha spindle rate during the auditory secondary task could be validated. We assume that visual processing of the driving scene was actively inhibited during listening to an audio book (Klimesch, 2007). A statistically significant lower alpha spindle rate during driving without secondary task and the lowest spindle rate during the visuomotor secondary task can be explained with the absence of acoustic stimuli and gradually increased visual information processing. Hence, a higher engagement of visual resources can be assumed. According to Birbaumer and Schmidt (2006), cortico-thalamic processes, indicated by alpha spindles, select instantaneously important parts of gathered information, so that especially during the additional auditory secondary task, mainly acoustic information can pass via medial geniculate nucleus, and visual information processing is actively inhibited. The wide and complex connection between the thalamus and the cerebral cortex allows for a high interaction playing an important part in shifting attention. In this study, a continuous shift of attention was required to perform both the secondary task and the primary driving task.

Cooper et al. (2003) could find similar responses of alpha-band activity during internalized attention. Alpha band power was significantly higher when participants had to imagine sequences of previously presented external stimuli as compared to simply attending to them. Participants actively inhibited visual information processing during internally directed attention. A different approach was followed by Foxe et al. (1998) who intentionally induced attention shifts by cueing attention before presenting an audio-visual stimulus. They suggested that ~10 Hz oscillations in parieto-occipital areas are affected by the direction and maintenance of visual attention. The same effect could be seen in our results, when participants divided their attention between the generally visual driving task and the auditory secondary task.

Auditory input does not necessarily impair visual attention. Dingus et al. (1995) investigated the driving behaviour while using different types of route guidance systems (auditory, visual). The authors found turn-by-turn instructions and accompanying voice guidance to be less cognitively demanding as compared to electronic route maps. The combination of visual and auditory instructions resulted in less abrupt brakings and lower workload.

The shortened spindle duration during the visuomotor secondary task as compared to driving only and the auditory secondary task presumably resulted from a highly demanding visual task, in which participants permanently had to switch between the driving task and the visual task on the in-vehicle display. Since the participants were driving in real traffic, they obviously preferred the primary driving task, but permanently shifted their attention to the secondary task resulting in a mean of 110 correctly identified distractors per block (three minutes). Both tasks generally included a high amount of visual input with little requirement of active inhibition of visual information.

Time-on-task

Time-on-task also had a significant impact on alpha spindle rate. Previous findings (Schmidt et al., 2009; Simon et al., 2011) have shown that there are long-term effects of fatigue on alpha spindle rate during monotonous daytime driving. In addition to short-term modulations of the alpha spindle rate, we also found a long-term increase caused by task-related fatigue. Even if participants were highly attentive to the driving and secondary tasks it can be assumed that there was a decreased processing of visual stimuli due to increasing fatigue. As a consequence, they were less attentive to the driving task in the last of the four blocks. An active inhibition of the cortical processing of visual stimuli caused by a task-related fatigue could be the reason for an increase in the spindle rate with prolonged driving duration.

Conclusion

Alpha spindle rate and *alpha spindle duration* proved to be suited measures to reliably differentiate between three different driver states, i.e. driving with auditory secondary task, driving with visuomotor secondary task and driving without secondary task. Supported by adequate pre-processing, i.e. a conducted artifact correction and signal compensation methods, they proved to be highly robust to ocular, muscular and technical artifacts and are available for on-line analysis from spontaneous EEG recordings.

Therefore they offer an objective and direct measure for cognitive driver state assessment of high ecological validity and practicability as compared to traditional indirect methods such as event-related based approaches (i.e. oddball paradigm) or subjective measures, such as verbal assessment of the driver state, which have a proven effect on objective indicators (Schmidt et al., 2011).

Our next goal is to develop an on-line classifier able to detect these three considerable mental driver states that might have a high impact on the current driving behaviour and reflect the driver’s ability to adequately attend to traffic.

Acknowledgements

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References

Birbaumer, N., & Schmidt, R. F. (Eds.) (2006). *Springer-Lehrbuch. Biologische Psychologie* (6., vollst. überarb. und erg. Aufl.). Heidelberg: Springer Medizin.

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

Broadbent, D.E. (1958). *Perception and communication.* Oxford: Pergamon Press.

Brookhuis, K. A., & Waard, D. de (2010). Monitoring drivers' mental workload in driving simulators using physiological measures: Assessing Safety with Driving Simulators. *Accident Analysis & Prevention, 42*(3)*,* 898–903.

CARE road accidents database (2009). *Road safety evoluation in EU*. Retrieved from http://ec.europa.eu/transport/road_safety/pdf/observatory/historical_evol.pdf.

Cohen, R. A. (1993). *The neuropsychology of attention. Critical issues in neuropsychology*. New York: Plenum Press.

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

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

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some Theoretical Considerations. *Psychological Review, 70*(1)*,* 80–90.

Dingus, T., McGehee, D., Hulse, M., Jahns, S., Manakkal, N., Mollenbauer, M., & Fleischman, R. (1995). *TravTek Evaluation Task C3: Camera Car Study*. Report FHWA-RD-94-076, Federal Highway Administration Office of Safety and Traffic Operations R&D. MacLean, VA.

Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J., et al. (2006). *The 100-Car Naturalistic Driving Study, Phase II: Results of the 100-Car Field Experiment*. DOT HS 810 593.

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

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

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55*(4)*,* 468–484.

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

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

Kahnemann, D. (1973). *Attention and Effort.* Englewood Cliffs, NJ: Prentice Hall.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews, 53*(1)*,* 63–88.

Papadelis, C., Chen, Z., Kourtidou-Papadeli, C., Bamidis, P. D., Chouvarda, I., Bekiaris, E., & Maglaveras, N. (2007). Monitoring sleepiness with on-board electrophysiological recordings for preventing sleep-deprived traffic accidents. *Clinical Neurophysiology, 118*(9), 1906–1922.

Pereda, E., Gamundi, A., Rial, R., & González, J. (1998). Non-linear behaviour of human EEG: fractal exponent versus correlation dimension in awake and sleep stages. *Neuroscience Letters*, *250*(2), 91-94. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9697926

Pfurtscheller, G. (2003). Induced Oscillations in the Alpha Band: Functional Meaning. *Epilepsia, 44,* 2–8.

Posner, M. I., & Rafal, R. D. (1987) Cognitive Theories of Attention and the Rehabilitation of attentional deficits. In M. J. Meier, A. L. Benton, & L. Diller (Eds.), *Neuropsychological Rehabilitation* (pp. 182–201). Edinburgh: Churchill Livingstone.

Reinoso-Suárez, F., Andrés, I. de, & Garzón, M. (Eds.) (2011). *Advances in Anatomy, Embryology and Cell Biology: Vol. 208*. *Functional Anatomy of the Sleep-Wakefulness Cycle: Wakefulness*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

Schlögl, A., Keinrath, C., Zimmermann, D., Scherer, R., Leeb, R., & Pfurtscheller, G. (2007). A fully automated correction method of EOG artifacts in EEG recordings. *Clinical Neurophysiology, 118*(1), 98–104.

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

Schmidt, E. A., Schrauf, M., Simon, M., Buchner, A., & Kincses, W. E. (2011). The short-term effect of verbally assessing drivers' state on vigilance indices during monotonous daytime driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 14,* 251–260.

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

Shaw, J. C. (2003). *The brain's alpha rhythms and the mind*. New York: Elsevier.

Sidak, Z. (1971). On probabilities of rectangles in multivariate Student distributions: Their dependence on correlations. *Ann. Math. Statist., Volume 42*(1), 169–175.

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

Statistisches Bundesamt (2010). *Verkehrsunfälle - Unfallentwicklung im Straßenverkehr 2009*. Wiesbaden.

Stutts, J. C., Reinfurt, D. W., Staplin, L., & Rodgman, E. A. (2001). *The role of driver distraction in traffic crashes*. Retrieved from http://www.aaafoundation.org/pdf/distraction.pdf.

van Dijk, H., Schoffelen, J.-M., Oostenveld, R., & Jensen, O. (2008). Prestimulus Oscillatory Activity in the Alpha Band Predicts Visual Discrimination Ability. *The Journal of Neuroscience, 28*(8), 1816–1823.

Wickens, V. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention.* Orlando: Academic Press.

Analysis and Single-Trial Classification of EEG Alpha Spindles on Prolonged Brake Reaction Times During Auditory Distraction in a Real Road Driving Study

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Abstract

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

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

1. Introduction

Driver distraction and inattention lead to a substantial number of traffic accidents. In 2009, 5474 people died in road accidents in the United States due to driver distraction, amounting to 16% of all fatal crashes. Additionally, 448.000 injuries where at least one form of driver distraction was noticed were registered in police crash reports (NHTSA, 2010). Natural driving studies, where drivers are monitored during everyday driving, revealed an even higher influence of driver distraction on crashes, though with a broader definition of inattention, including fatigue among other things (Klauer et al., 2006). These authors reported distraction was responsible for 78% of crashes and 65% of near-crashes for automobiles. Olsen et al. (2009) found distraction a contributing factor in 71% of crashes and 46% of near-crashes for heavy trucks. These naturalistic driving studies are based mainly on video analysis, a radar system, lane tracking and vehicle data in predefined safety-critical events related to randomly chosen baselines. While this approach has a high ecological validity and apparently identifies observable distraction, it is not possible to identify internally directed attention which is also known as daydreaming or highway-hypnosis (Wertheim, 1991). A stimulus presented in the eye-field of a person heading to that stimulus is not necessarily attended and consciously perceived. This so-called “looked-but-failed-to-see” phenomenon is a major cause of accidents (Herslund et al., 2003). Since cognitive resources are often divided among various tasks besides that of driving, information is not always processed with the same quality. In regions over the pre-frontal and parietal cortex, decision is made about the importance of a stimulus and whether attention should be paid to it (Birbaumer & Schmidt, 2006). If the incoming distraction is rated more important than the primary driving task, then parts of the attention resources are shifted to the current secondary task.

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

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

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

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

The aim of the present study is to identify neurophysiological correlates of driver distraction as well as the influence of distraction on reaction times to emergency braking. In order to maximise ecological validity, the experiment was conducted in real cars on a non-public test track. Additionally, machine learning methods were used to investigate whether the identified neural correlates can be used to predict driver distraction on a single-trial level.

Hypothesis

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

(a) Therefore, *driving with auditory secondary task* is expected to increase brake reaction times and alpha spindle rate as compared to *driving only*.

(b) With ongoing *time-on-task*, brake reaction times as well as alpha spindle rate are expected to increase due to task-related fatigue.

(c) Alpha spindle rate is expected to predict driver distraction on a single-trial level (i.e., three-minute-block).

2. Methods:

2.1 Participants

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

2.2 Driving task (primary task)

The study was conducted on a non-public test track in an unused military training area in Münsingen, Germany. Participants were instructed to always prioritize the primary task and to drive in accordance with official traffic regulations. They had to drive three rounds on the test track , one round being 37 km long with distinct variations in road curvature and altitude. The setup consisted of two Mercedes-Benz S-Class cars: The lead car was navigated by an investigator and the following car was driven by the participant. Participants were instructed to follow the lead car at a constant distance of approximately 20 m at a maximum speed of 60 km/h. In order to obtain a reference for the required distance, the participant's car was parked 20 m behind the lead car before the start of the experiment. The investigator initiated emergency braking with an interstimulus interval of 42.5 s to 57.5 s (M = 50 s, uniformly distributed jitter) after receiving an acoustic trigger from a laptop, provided that the lead car had a constant velocity of 60 km/h and adequate separation to the trailing vehicle. Given the lead car's abrupt braking from 60 km/h to 40 km/h, the participant was instructed also to brake immediately as soon as the brake light of the lead car flashed, irrespective of the actual distance between cars. After every emergency braking, the investigator accelerated back to 60 km/h using cruise control.

2.3 Auditory secondary task

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

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

2.4 Test procedure

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

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

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

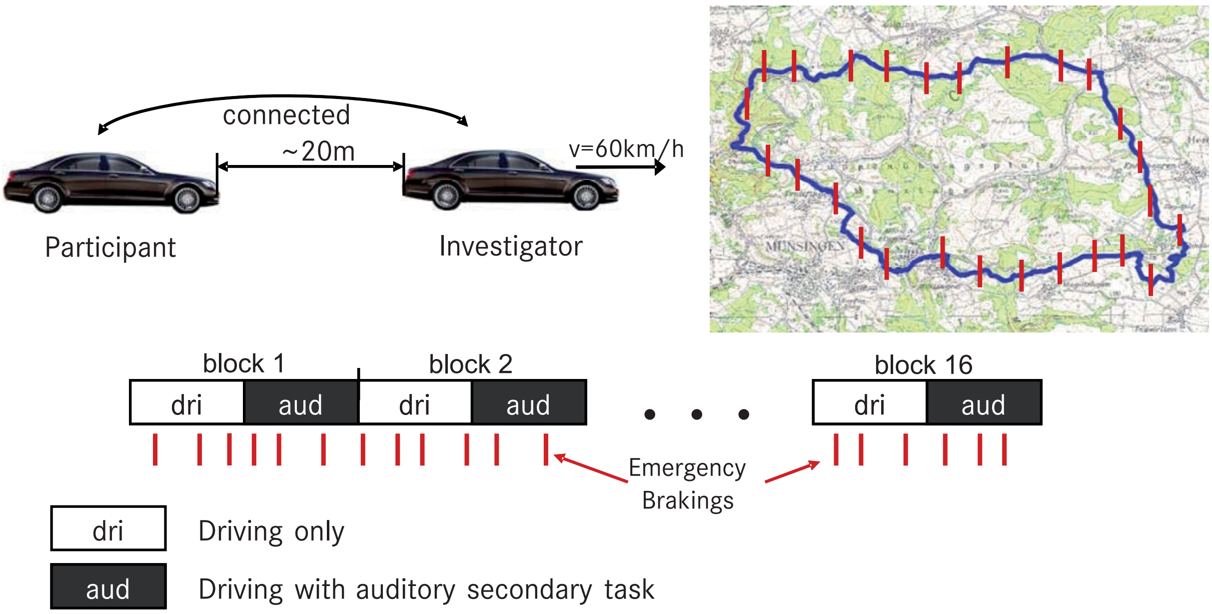

Fig. 1: Test procedure of the car following task. The participant followed the investigator in the leading car with 60 km/h at a distance of approximately 20 m for three rounds on the test track. Alternately participants drove without or with auditory secondary task.

2.5 Physiological recordings

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

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

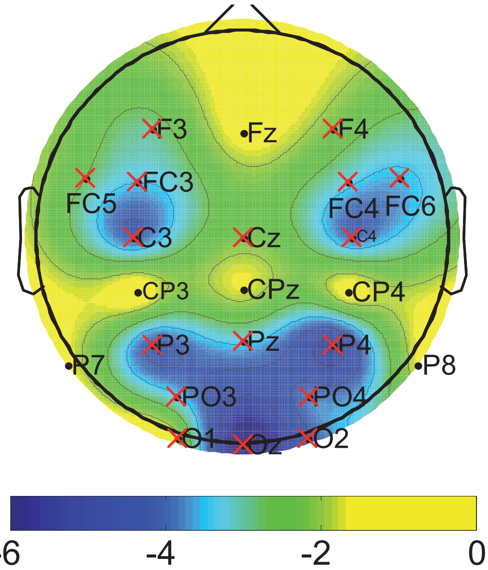

Fig. 2: Topoplot of recorded channels. Channels for the selected cluster are marked with a red cross (17 channels). Colours represent the test statistics of t-tests between *driving with auditory secondary task* and *driving only* for each channel.

2.6 Pre-processing

EEG data was re-referenced offline to common average.

Changes in alpha spindle rate due to distraction were analyzed with a nonparametric cluster-based permutation test (Maris & Oostenveld, 2007). In this way, clusters of spatially contiguous channels can be identified without the necessity of predefined channel. T-tests for the variable distraction are calculated for each channel and significant channels are concentrated on one cluster. Alpha spindle parameters of EEG-channels from the significant cluster (Fig. 2) were averaged, while EEG-channels Fz, CP3, CPz, CP4, P7, P8, T7 and T8 were excluded from further analysis.

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

In order to minimize the influence of muscular and technical artifacts, 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.

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

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

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

2.7 Experimental Design

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

An a priori statistical power analysis using G*Power 3.1.2 (Faul et al., 2007) showed that in order to detect differences of $f = .40$ between the two levels of the *distraction* variable given a correlation between the levels of this repeated measures variable of $\rho = .5$, a nonsphericity correction of $\varepsilon = 1.0$, and $\alpha = \beta = .05$, a total sample size of 23 was needed. A post-hoc power analysis showed that given a final sample of $N = 20$, the power $(1 - \beta)$ was .92 which we consider adequate.

A repeated-measures analysis of variance (ANOVA) was used for all within-subject comparisons to identify the effect of *time-on-task* and *distraction* on each dependent measure. Seven datasets had to be excluded from further analysis due to missing values for *EMG reaction times*, and another four due to missing values for *distance between cars*. The level of α was set to .05 for all analyses. Whenever H_0 had to be rejected, the partial η^2 is reported as a measure of relative effect size. Statistically significant results of the *distraction* variable were subjected to post-hoc analysis using comparison of simple main effects by one-step Sidak (Sidak, 1971). For the *time-on-task* variable, a post-hoc trend analysis was calculated using polynomial contrasts. Only significant differences and trends are reported.

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

3. Results

3.1 Data reduction

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

3.2 Auditory secondary task

For the auditory task, participants found 70.5% of all predetermined words (“die”, “und”) in the text, and they could answer 75.1% of all questions correctly. No effects of *time-on-task* could be found for the auditory secondary task.

3.3 Main results

3.3.1 EEG alpha spindle parameters

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

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

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

		Main effect			Trend analysis (polynomial)			
Factor	**Measure**	**F(15,285)**	**p**	**η²**	**Type**	**F**	**p**	**η²**
time-on-task	spindle rate	2.270	<.01	.107	Quadr.	8.75	<.01	.315
	spindle duration	4.429	<.001	.189	Linear	5.49	<.05	.224
	spindle frequency	2.386	<.01	.112	Linear	8.34	<.01	.305
	brake reaction time	9.304	<.001	.329	Linear	76.0	<.001	.800
	muscular response	1.692	ns.					
	distance	1.164	ns.					
		Main effect			**Pairwise comparison (Sidak)**			
Factor	**Measure**	**F(1,19)**	**p**	**η²**	**Post-hoc effect**			
dis-traction	spindle rate	12.407	<.01	.395	auditory > driving			
	spindle duration	2.202	ns.					
	spindle frequency	1.928	ns.					
	brake reaction time	20.833	<.001	.523	auditory > driving			
	muscular response	14.188	<.01	.542	auditory > driving			
	distance	2.160	ns.					

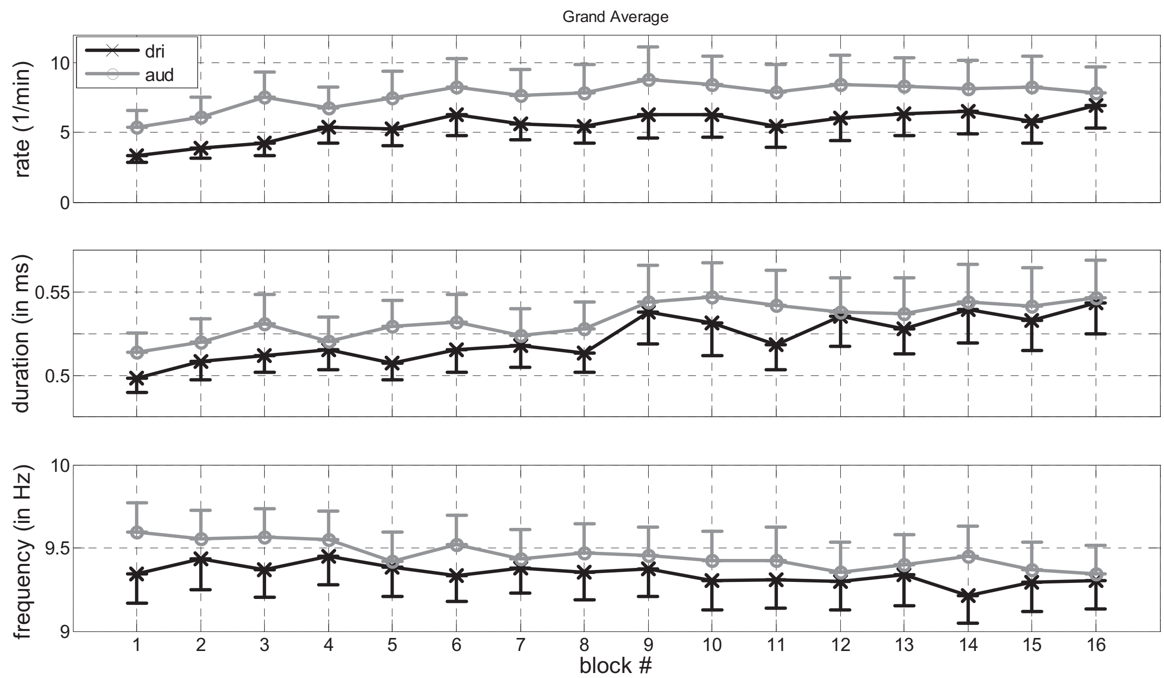

Fig. 3: Chronological sequence of alpha spindle rate (top panel), duration (center panel), and of frequency for driving only (dri) and driving with auditory secondary task (aud)

3.3.2 Brake reaction times

Fig. 4 shows the brake reaction time as an indicator for driving performance. Braking was significantly slower when *driving with auditory secondary task* (M = 803 ms, SE = 27.7 ms) as opposed to *driving only* (M = 728 ms, SE = 17.6 ms; $F(1,19)=20.833$, $p<.001$, $\eta^2=.523$).

For the *time-on-task* variable, polynomial trend analysis showed a significant linear increase with time of driving ($F(1,19)=75.992$, $p<.001$, $\eta^2=.800$).

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

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

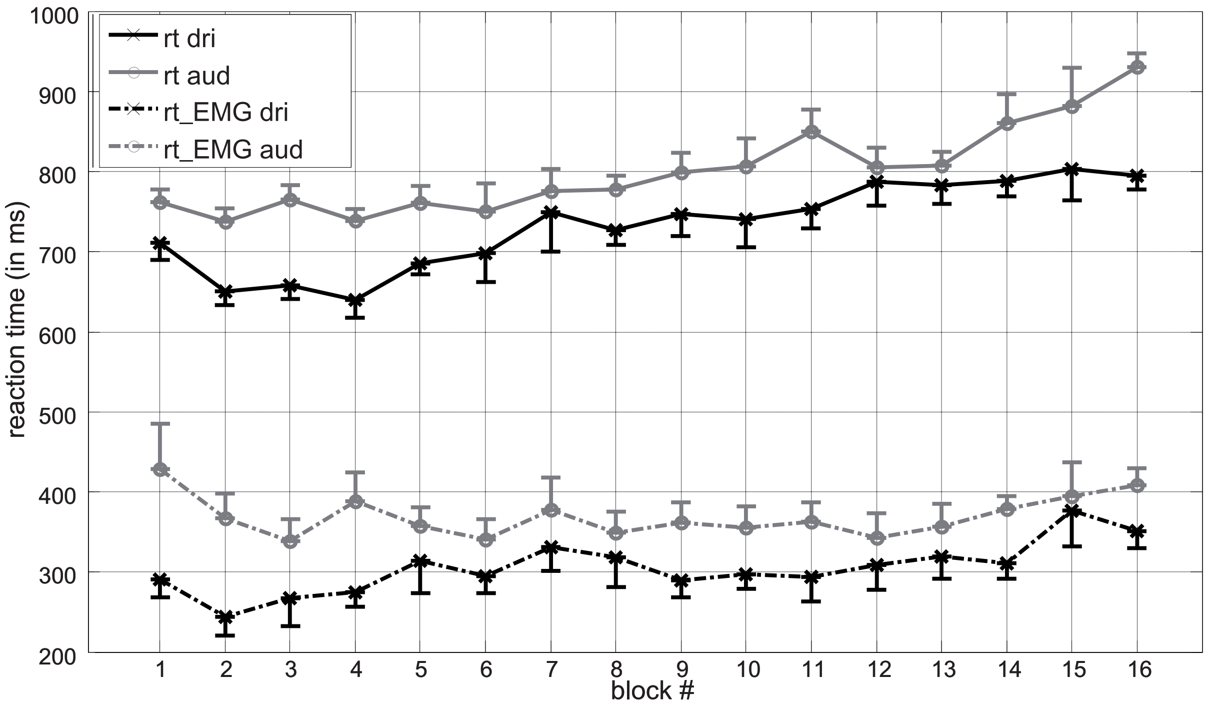

Fig. 4: Upper two curves: Brake reaction times for conditions driving only (rt dri) and driving with auditory secondary task (rt aud);
Lower two curves: EMG reaction times for conditions driving only (rt_EMG dri) and driving with auditory secondary task (rt_EMG aud).

The *time-on-task* variable had no significant impact on the *distance between cars* (*F*(2.174,225)=1.164, ns.). However, participants kept a larger separation distance at the beginning (first block: M = 18.2 m, SE = 1.08 m) compared to the end of the drive (last block: M = 16.1 m, SE = .98 m), with an unsystematic decrease over time. A linear basic fit showed a decrease of distance of 0.15 m per block.

3.4 Classification

Classification was performed for all combinations of alpha spindle parameters (i.e., rate, amplitude, frequency and duration) and was able to discriminate between the two conditions of distraction (*driving with auditory secondary task, driving only*). Further, classification error decreased for combined multiple features. The analysis therefore focused on the feature sets comprising three and four alpha spindle parameters. The classification error for each subject and each feature set, along with means and median, is shown in Fig. 5. The combination of all four spindle parameters tended to yield the best performance of about 8% classification error.

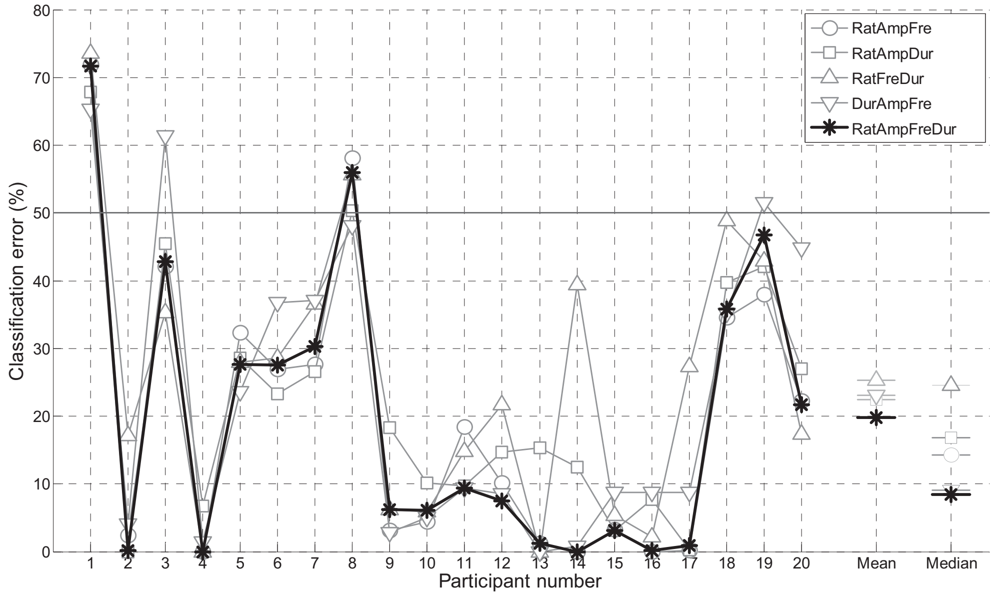

Fig 5: Classification error for each subject and for different combinations of alpha spindle parameters. Best median performance (8% classification error) is obtained for the combination of all four parameters (asterisk). The different combinations are specified in the legend. The dashed line at 50% classification error indicates chance performance. (Rat=rate; Amp=amplitude; Fre=frequency; Dur=duration).

4. Discussion

4.1 Distraction

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

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

In Fig. 6, EMG activity is illustrated for a total of 132 brake reactions of one participant. The prolonged brake reaction times can be explained by slower and less intensive muscle contractions. Mean EMG reaction time was measured at 337 ms (SE = 16.5 ms).

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

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

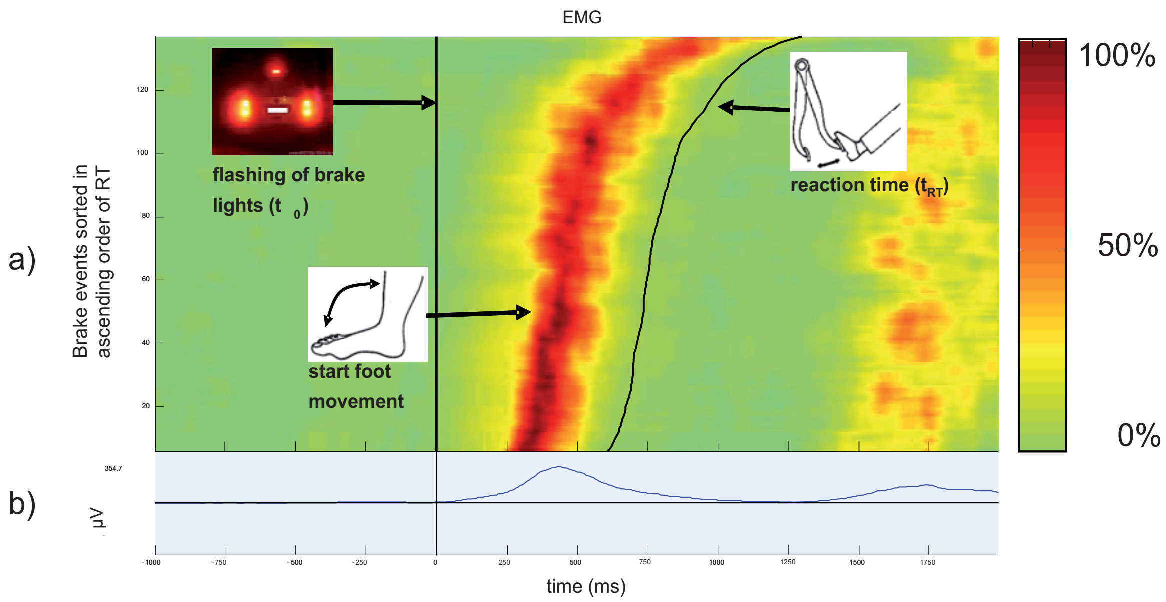

Fig. 6: Chronological sequence of the EMG intensity signal of one subject (*N=1*) during his 132 braking events starting 1000 ms prior to the flashing of the brake lights (t_0=0 ms), and ending 2000 ms thereafter. The icons describe the action and their arrows point to the associated time. a) Upper graph: EMG signal of 132 events sorted in ascending order (i.e. #1 the fastest, # 132 the slowest) and baseline corrected to the period 1 s prior to the stimulus. The power of the EMG signal is colour coded (see legend on the right) between 0% showing no muscular action and 100% representing the maximal EMG signal obtained for this subject.
b) Lower graph: Shows the average of all 132 EMG brake reactions of this participant. An increase of muscle activity can be observed after about 250 ms. Participants showed another increase in EMG activity at about 1500 ms due to their right foot lift to return back to the gas pedal.

4.2 Time-on-task

Next to short-term variations in the alpha spindle rate that may indicate phasic cognitive processes (e.g., distraction from monotonous monitoring tasks like highway driving), Schmidt et al. (2009) and Simon et al. (2011) reported that fatigue had a rather long-term effect on the alpha spindle rate. In this study, strong effects of *time-on-task* could also be seen in the alpha spindle rate and in the brake reaction times. Brake reaction times increased linearly while alpha spindle rate showed a quadratic increase in polynomial trend analysis. After half of the drive, a ceiling effect could be seen for the increase of alpha spindle rate (see Fig. 3). Since EMG reaction times did not significantly increase over time, longer movement duration from lifting the right foot from the gas pedal until the actual movement of the brake pedal is responsible for longer total brake reaction times. This possibly originates from a habituation effect or an emotional blunting due to task-related fatigue.

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

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

Since the drivers are still aware of the driving task, a minimal amount of visual information processing is still necessary to drive a car and to react to flashing brake lights. Hence, these restrictions could also be the reason for the observed ceiling effect.

4.3 Classification

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

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

5. Conclusion

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

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

6. Acknowledgements:

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7. References

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

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

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

Burkhardt, M. (1985). *Reaktionszeiten bei Notbremsvorgängen*. Verlag TÜV Rheinland.

Cohen, R. A. (1993). *The neuropsychology of attention*. *Critical issues in neuropsychology*. New York: Plenum Press.

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

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

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

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

Gevins, A., Smith, M. E., Leong, H., McEvoy, L., Whitfield, S., Du, R., & Rush, G. (1998). Monitoring Working Memory Load during Computer-Based Tasks with EEG Pattern Recognition Methods. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 40*(1)*,* 79–91.

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

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

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

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data (Report No. DOT HS 810 594)*. National Highway Traffic Safety Administration, USDOT. Retrieved from http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/Driver%20Distraction/810594.pdf.

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

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

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

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

Olson, R. L., Hanowski, R. J., Hickman, J. S., & Bocanegra, J. *Driver Distraction in Commercial Vehicle Operations*. (Document no. FMCSA-RRT-09-042). Federal Motor Carrier Safety Administration, USDOT. Retrieved from http://www.fmcsa.dot.gov/facts-research/research-technology/report/FMCSA-RRR-09-042.pdf.

Pfurtscheller, G. (2003). Induced Oscillations in the Alpha Band: Functional Meaning. *Epilepsia, 44,* 2–8.

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

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

Schmidt, R. F., Thews, G., & Lang, F. (Eds.) (2000). *Physiologie des Menschen* (28. korrigierte und aktualisierte Auflage). Berlin: Springer.

Shaw, J. C. (2003). *The brain's alpha rhythms and the mind*. New York: Elsevier.

Sidak, Z. (1971). On probabilities of rectangles in multivariate Student distributions: Their dependence on correlations. *Ann. Math. Statist., Volume 42*(1)*,* 169–175.

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

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

Strayer, D. L., Drews, F. A., & Crouch, D. J. (2006). A comparison of the cell phone driver and the drunk driver. *Hum. Factors, 48*(2)*,* 381–391.

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