Improving passive driver fatigue, sitting health risk factors and user experience in automobiles.

Concept~~io~~n, development and evaluation of a novel interactive seating system.

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I hope my work can contribute to making the (automotive) world healthier and safer.

Abstract

Long journeys in automobiles are often accompanied by monotony-related fatigue due to lack of stimulation as well as physical health risks due to prolonged sitting. In the literature, cognitive secondary tasks have been proposed as a countermeasure against monotony-related fatigue. State-of-the-art measures to reduce health-risks mainly include seating systems that passively mobilize the passenger.

With the aim of increasing driving safety while reducing health risks, a novel interactive seating system (IASS) was conceptualized, developed and evaluated. The IASS is designed to motivate the driver or passengers to interact with the seat through active movements against the seat surface. Unlike current interactive seating systems, the basic interaction of the IASS is not via a display. Instead, auditory instructions, air bladders in the seat back, vibration motors and ambient lighting are used for interaction. A display is only used for introducing the use of the system or as a complementary interaction element for the passengers. This allows the driver to keep his or her eyes, and therefore attention, on the road. As a result, in contrast to the state of the art, the system should be suitable not only for passengers but also for the driver. This in turn opens up the possibility of using the IASS as a secondary task while driving to counteract a monotony-related reduction in attention. It should be noted that the increased driving safety due to improved attention serves not only the occupants but also other road users. At the same time, all passengers have the opportunity to reduce the health risks associated with prolonged sitting by making physiologically beneficial movements against the seat.

A total of three studies were conducted to develop and evaluate the IASS.

The first study was necessary to develop the IASS. In order to detect the passenger's movements during interaction, pressure sensors were to be integrated into the seat back. To ensure reliable movement detection of passengers with different anthropometries, it was crucial to place the sensors at optimal positions in the backrest. Therefore, the first step in the development of the IASS was to conduct a study to determine these optimal positions. Within the study, seat pressure distribution images were captured and subsequently analyzed using *Statistical Parametric Mapping*. This is a statistical method that is

usually used in functional magnetic resonance imaging. In the study, the method was used for the first time to evaluate seat pressure distribution images. The advantage over conventional methods for analyzing seat pressure distribution images is the high spatial resolution. This made it possible to precisely define the sensor locations.

Based on the information obtained in the first study, the IASS was set up. Afterwards, two additional studies were conducted to compare the IASS with a current seat massage system (MS).

The second study was to evaluate the potential of the IASS for driving safety. The driving simulator study showed that the IASS reduced monotony-related fatigue, whereas this was not the case when using the MS. The IASS was also preferred over the MS in terms of user experience as well as emotional perception. In addition, subjects rated the IASS as better at increasing comfort and decreasing discomfort compared to the MS.

The third and final study examined whether the IASS was better than the MS at counteracting the physical health risks associated with prolonged sitting. For this purpose, both seating systems were installed in a production vehicle. In order to compare the effects of both seating systems, health-related parameters were recorded. The study was conducted in a stationary vehicle to exclude signal interference caused by driving. The electrocardiogram showed that only the IASS increased the heart rate. Electromyographic measurements also showed that the IASS increased activity in the six muscles recorded, whereas with the MS only one muscle showed a trend toward increased activity. Accordingly, the health-promoting effects of the IASS can be considered much higher compared to the MS.

To the author's knowledge, this is the first scientific publication to investigate a secondary motor task as a measure against monotony-related fatigue in the vehicle. In addition, it is the first direct comparison of whether an automotive seating system that encourages active movement is superior to a system that passively moves the passenger in terms of reducing the negative physical effects of sitting.

Deutsche Kurzfassung

Lange Fahrten in Automobilen werden oftmals von monotoniebedingter Ermüdung durch mangelnde Stimulation sowie körperlichen Gesundheitsrisiken durch langanhaltendes Sitzen begleitet. In der Literatur werden kognitive Zusatzaufgaben als Maßnahme gegen monotoniebedingte Ermüdung vorgeschlagen. Der Stand der Technik um gesundheitliche Risiken durch langanhaltendes Sitzen im Fahrzeug zu reduzieren, beschränkt sich hauptsächlich auf Sitzsysteme, welche die Passagiere passiv mobilisieren.

Mit dem Ziel die Fahrsicherheit zu erhöhen und gleichzeitig Gesundheitsrisiken zu reduzieren, wurde ein neuartiges interaktives Sitzsystem (IASS) konzipiert, entwickelt und evaluiert. Das IASS soll den Fahrer/die Fahrerin oder die Passagiere dazu motivieren mit dem Sitz zu interagieren und dabei aktive Bewegungen gegen die Sitzfläche auszuführen. Im Gegensatz zu aktuellen interaktiven Sitzsystemen erfolgt die grundlegende Interaktion nicht über ein Display. Stattdessen werden auditive Einsprachen, Luftblasen in der Lehne, Vibrationsmotoren sowie die Ambientebeleuchtung genutzt. Ein Display kommt lediglich bei der Einführung in die Nutzung des Systems oder ergänzend für die Passagiere zum Einsatz. Das ermöglicht, dass der Fahrer/die Fahrerin den Blick und damit auch die Aufmerksamkeit auf der Straße behalten kann. Dadurch soll das System, im Gegensatz zum Stand der Technik, nicht nur für die Passagiere, sondern auch für den Fahrer/die Fahrerin geeignet sein. Das wiederum eröffnet die Möglichkeit das IASS als Zusatzaufgabe neben dem Fahren zu nutzen, um einer monotoniebedingten Reduktion der Aufmerksamkeit entgegenzuwirken. Dabei ist anzumerken, dass die erhöhte Fahrsicherheit durch eine verbesserte Aufmerksamkeit nicht nur den Insassen, sondern auch den anderen Verkehrsteilnehmern dient. Gleichzeitig haben alle Passagiere die Möglichkeit, durch die physiologisch sinnvollen Bewegungen gegen den Sitz, die Gesundheitsrisiken durch langanhaltendes Sitzen zu reduzieren.

Insgesamt wurden drei Probandenstudien durchgeführt, um das IASS zu entwickeln und zu evaluieren.

Die erste Probandenstudie diente der Entwicklung des IASS. Um die Bewegungen des Passagiers/der Passagierin bei der Interaktion zu detektieren, wurden Drucksensoren in der Sitzlehne integriert. Zur Gewährleistung einer zuverlässigen Bewegungserkennung von Passagieren mit unterschiedlichen anthropometrischen Merkmalen, war es entscheidend, die Sensoren an optimalen Positionen in der Lehne zu platzieren. Daher war der erste Schritt im Entwicklungsprozess des IASS die Durchführung einer Probandenstudie, um diese optimalen Positionen festzulegen. Im Rahmen der Studie wurden Sitzdruckverteilungsbilder erfasst und anschließend mit einer Methode, dem *Statistical Parametric Mapping* ausgewertet, die für gewöhnlich bei der funktionellen Magnetresonanztomographie eingesetzt wird. In der vorliegenden Arbeit wurde diese Methode erstmalig zur Auswertung von Sitzdruckverteilungen herangezogen. Der Vorteil gegenüber herkömmlichen Methoden ist die hohe örtliche Auflösung. Damit war es möglich, die Sensoranbringungspunkte sehr präzise zu definieren.

Anschließend wurde das IASS auf Basis der in der ersten Studie gewonnenen Information aufgebaut und anschließend in zwei weiteren Probandenstudien mit einem aktuellen Sitzmassagesystem (MS) hinsichtlich Wirksamkeit verglichen.

In der zweiten Probandestudie sollte das Potential des IASS für die Fahrsicherheit bewertet werden. Die im Fahrsimulator durchgeführte Studie zeigte, dass das IASS die monotoniebedingte Ermüdung reduzierte, während dieser Effekt bei Nutzung des MS nicht auftrat. Das IASS wurde ebenfalls bezüglich des Nutzererlebnisses sowie der emotionalen Wahrnehmung gegenüber dem MS bevorzugt. Außerdem bewerteten die Probanden und Probandinnen, dass das IASS im Vergleich zum MS, sowohl Komfort wesentlich stärker erhöhte als auch Diskomfort stärker reduzierte.

In der dritten und abschließenden Probandenstudie wurde untersucht, ob das IASS den körperlichen Gesundheitsrisiken durch langanhaltendes Sitzen besser entgegen wirkt als das MS. Hierfür wurden beide Sitzsysteme in einem Serienfahrzeug verbaut. Um die Effekte beider Sitzsysteme zu vergleichen, wurden gesundheitsrelevante Parameter erfasst. Damit fahrtbedingte Signalstörungen ausgeschlossen werden konnten, wurde die Studie im stehenden Fahrzeug durchgeführt. Das

Elektrokardiogramm zeigte, dass ausschließlich das IASS die Herzfrequenz erhöhte. Elektromyographische Messungen zeigten außerdem, dass das IASS die Aktivität in den sechs erfassten Muskeln erhöhte, während beim MS lediglich ein Muskel eine Tendenz zur Aktivitätserhöhung zeigte. Entsprechend sind die gesundheitsfördernden Effekte des IASS im Vergleich zum MS als wesentlich stärker einzustufen.

Nach dem Kenntnisstand des Autors, ist dies die erste wissenschaftliche Publikation welche eine motorische Zusatzaufgabe als Maßnahme gegen monotoniebedingte Ermüdung im Fahrzeug untersucht. Darüber hinaus wurde erstmalig direkt verglichen, ob ein automobiles Sitzsystem welches zu aktiven Bewegungen animiert, einem System das die Passagiere passiv bewegt, hinsichtlich der Reduktion der negativen körperlichen Effekte des Sitzens überlegen ist.

Table of contents

List of abbreviations

AB	Air bladder
AC	Active condition
ADSS	Active dynamic seating system
BD	Blink duration
BF	Blink frequency
bpm	Beats per minute
CC	Control condition
CLBP	Chronic lumbar back pain
ECG	Electrocardiography
ED	Eyelid distance
EMG	Electromyography
HR	Heart rate
HRV	Heart rate variability
IASS	Interactive seating system
KSS	Karolinska sleepiness scale
m.	Musculus
MDFL	Mean departure from lane
MET	Metabolic equivalent
MS	Massage seating system
MSP	Musculoskeletal pain
MVC	Maximum voluntary contraction
PC	Passive condition
PD	Pupil diameter

PDF	Passive driver fatigue
PDSS	Passive dynamic seating system
RMS	Root-mean-square
SCL	Skin conductance level
SD	Standard deviation
SDLP	Standard deviation of lane position
SDSA	Standard deviation of steering angle
SPDI	Seat pressure distribution image
SPM	Statistical Parametric Mapping
TI	Time interval

1. Introduction

This thesis describes the conception, development and evaluation of a novel interactive seating system (IASS) for automobiles. As illustrated in Figure 1, the IASS mainly aims to improve two issues that occur during long journeys in automobiles. The first aim is to attenuate monotony-induced fatigue, also referred to as passive driver fatigue (PDF); the second aim is to reduce negative physical effects through prolonged static sitting in the vehicle. Since the passengers benefit the most from the system if they use it regularly, a good overall user experience is also of relevance. The overall user experience can be influenced: (1) directly through the seating system or (2) indirectly through factors that are associated with the negative physical effects of static sitting or PDF. The interactive seating system in turn intends to influence these associated factors. User experience is generally a broad concept, that is defined as „the user's perceptions and responses that result from the use and/or anticipated use of a system, product or service" by the International Organization for Standardization (2018, p. 19). Based on this definition, user experience also includes aspects such as comfort or discomfort. In order to specify the relevant factors more precisely in this thesis, a distinction is made between user experience and overall user experience (see Figure 1). User experience alone refers to the specific questions that were asked in the user experience questionnaire of the study in Chapter 7. Overall user experience, on the other hand, describes sitting comfort and discomfort, emotional perception and user experience.

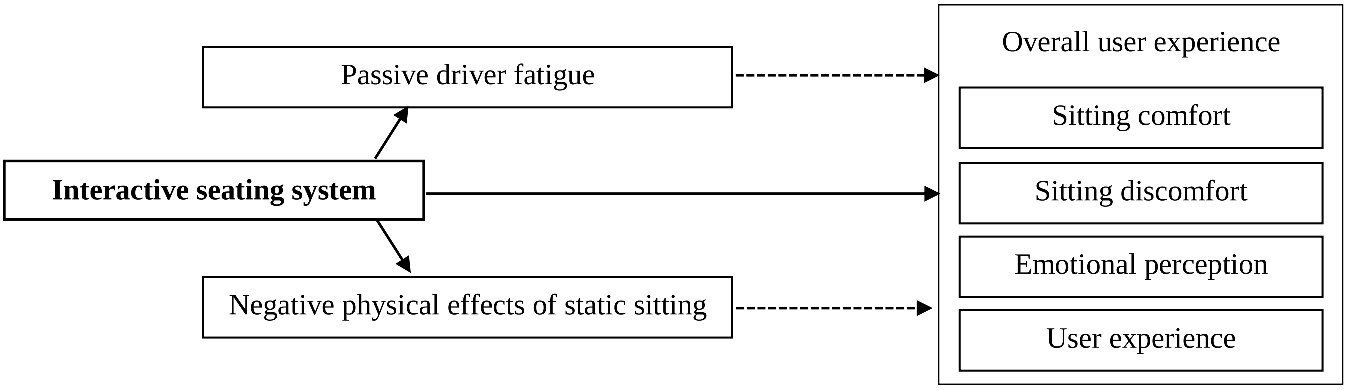

Figure 1: *Schematic representation of the factors that the interactive seating systems aims to improve.*

The present thesis is structured as follows. In the beginning, Chapter 2 and 3 present current scientific literature regarding PDF and negative physical effects of static sitting in automobiles. This literature review includes influencing factors, measuring methods as well as current countermeasures. Based on the findings from Chapter 2 and 3, Chapter 4 describes the novelty in the concept of the interactive seating system. This concept makes it necessary to integrate pressure sensors in the seat back to detect movements of the passenger. The optimal location of these sensors in the seat back is essential to build up the seating system. That is why, these locations were accurately defined with a study that is described in Chapter 5. Based on the findings of the study, a prototype of the IASS was build up, which is described in Chapter 6. This prototype was also used for the following evaluation studies in which the IASS was compared with a state-of-the-art massage seating system. Chapter 7 reports the first evaluation study that was conducted in a driving simulator. This study had the primary goal to compare the seating systems regarding their influence on passive driver fatigue. In addition, different aspects of the overall user experience were evaluated. The second evaluation study, which is described in Chapter 8, investigated the influence of the seating systems on the negative physical effects of static sitting. Therefore, muscular and cardiorespiratory activity were measured in the vehicle. Chapter 9 summarizes the key findings of this thesis and discusses potential further steps. These further steps relate on the one hand to the development of the seating system and on the other hand to additional evaluation studies.

2. Weariness as a risk factor in road traffic

Chapter 2, 2.2.2, 2.5.2.1 and 2.5.2.3 were partially published in a largely similar form in Lampe & Deml (2022b).

According to the World Health Organization (2018), the worldwide number of road traffic deaths per year reached 1.35 million in 2016 and continues to rise steadily. Among children and young adults aged between 5 to 29 years, road traffic injuries are the leading cause of death. It is assumed that approximately 10 - 20% of all fatal crashes are fatigue-related (Dobbie, 2002; J. Horne & Reyner, 2001; MacLean et al., 2003; Philip, 2001; E. A. Schmidt et al., 2009; G. Zhang et al., 2016). However, the numbers could be severely underreported (Garbarino et al., 2001). Weariness-related accidents are difficult to detect, therefore it is common to use very conservative exclusion criteria for their classification. As soon as other risk factors, such as rain, are present, the accident is no longer classified as weariness-related. For this reason, most of the crash data report accidents, in which weariness was the only cause of the accident (J. A. Horne & Reyner, 1995; Philip, 2001). This approach appears additionally critical by the fact that weariness-related accidents can often also be the result of multiple factors. For example, even low alcohol consumption can increase the risk of sleep-related accidents (Banks et al., 2004).

Despite this limitation, weariness is seen as one of the most important causes of road crashes alongside with alcohol, speeding and distraction (Bener et al., 2017; Sagberg et al., 2004). Weariness-related accidents especially occur on highways, which often results in serious consequences due to high impact speeds (J. Horne & Reyner, 2001). In those crashes, the vehicle typically runs off the road or hits the back of another vehicle without a braking maneuver beforehand. Vanlaar et al. (2008) conducted a public opinion poll of Ontario drivers (N = 750) to collect information on attitudes, opinions and practices on fatigue and drowsy driving. Among the respondents, 58.6 % admitted that they occasionally drive while being fatigued or drowsy, 14.5 % stated that they had fallen asleep or ‘nodded off’ while driving, 1.9 % were involved in a fatigue or drowsiness related crash in the past year. Beirness et al. (2005) conducted a telephone interview (N = 1209) which revealed, that one fifth of the Canadian drivers had nodded off or fallen asleep at least once while driving in the past 12 months. Pack et al. (1995) identified characteristics of sleep-related crashes by analyzing data from the crash reporting system in North Carolina for the years 1990 - 1992. The study analyzed 4333 crashes in which the driver was judged asleep but not intoxicated. Weariness-related crashes predominantly involved a single vehicle (78 %), happened on roadways with higher speeds (62 % over 55 mph) and included a vehicle leaving the road (79 %). The drivers are mostly male (74.5 %) and young with a median age of 23.5 years. The frequency of sleep-related crashes peaks twice in 24 hours. The first peak is at early morning around 7:00 am in which mainly young drivers up to 45 years have accidents. The second peak is at mid afternoon around 3:00 pm with mostly old drivers over 45 years. Nabi et al. (2006) queried 13674 French drivers of whom 36 % reported that they had driven while being sleepy a few times within the last year. Furthermore, they found that the risk to be involved in a sleep related crash increased proportionally with the frequency of self-reported driving while being sleepy. This relationship is also reported by Bener et al. (2017). Based on the Manchester driver behavior questionnaire (Reason et al., 1990) which was conducted with 1545 participants, they found a significant relationship between injury involvement in vehicle crashes and sleepiness. The findings are further supported by Connor (2002) who assumes, based on interviews and questionnaires, that the incidence of injury crashes could be reduced by 19 % with the avoidance of sleepiness behind the wheel. Herman et al. (2014) calculated that the odds for crashes that involved injuries increased by factor 6 both for drivers that were not fully alert or sleepy and for drivers that slept less than 6h during the previous 24 hours before the crash.

Accidents caused by a loss of alertness or falling asleep are obviously a massive problem. Different factors lead to those accidents. Primarily, fatigue and sleepiness are mentioned. However, both terms are not always seen as separated concepts and are partially used synonymously such as in Bener et al. (2017), Dinges (1995) and Eoh et al. (2005). This problem is also stated by Vanlaar et al. (2008) who summarize that fatigue and sleepiness have different causes and are controlled by different processes.

Beirness et al. (2005) also define sleepiness and fatigue as closely related but distinct and separate concepts. The reason why both terms are often interchangeable used is the fact, that the result of both are the same (Beirness et al., 2005; Vanlaar et al., 2008). The fatigued or sleepy person becomes less attentive or alert and can at worst, fall asleep. Consequently, the ability to drive the vehicle safely can be impaired.

While this distinction might be of little relevance in everyday speech, a clear definition of both terms is necessary to address the resulting safety risks. Only in this way, the systematic development of countermeasures is possible. Therefore, the terms sleepiness and fatigue will be defined in Chapter 2.1 and 2.2. Afterwards in Chapter 2.3, both states will be brought together into one model that uses weariness as a superordinate term. In the present thesis, the term *weariness* refers to the phenomenon of reduced alertness due to both *fatigue* and *sleepiness*. The use of the superordinate term weariness may be necessary because it is often not possible to clearly determine the extent to which fatigue or sleepiness is the cause of the loss of attention. In most cases, it is likely to be a combination of both.

The authors of the literature that is reported in the following have partially used the terms sleepiness and fatigue differently from the definition in this thesis. Sometimes the authors also used the term drowsiness to describe one of both states. In these cases, the findings are reported using the terms in accordance with the definition of the present thesis.

2.1 Sleepiness

As the term ‘sleepiness’ indicates, it refers to factors that are directly related to the urge to sleep. Sleepiness is described as an interaction of circadian rhythm and wakefulness (Borbély, 1982; Borbély et al., 2016; Neu et al., 2010). Dawson & Reid (1997) compared the impairment of alcohol and reduced sleep in a laboratory visuomotor task. Between the tenth and twenty-sixth hour of wakefulness, performance decreased by 0.74 % per hour. The impairment after 17 hours of wakefulness was equivalent to 0.05 % of alcohol concentration and after 24 hours to 0.1 %. These are worrying results even though they might not directly be transferable to the more complex visuomotor task of driving. However, the negative impact of insufficient sleep or prolonged wakefulness has been observed in driving studies as well. Åkerstedt &

Folkard (1995) validated the model described in Borbély et al. (2016) with sleep data from truck drivers, train drivers and laboratory subjects. Based on the data, they achieved a high accuracy in the prediction of alpha-power density from electroencephalography, a measure that is highly related to subjective weariness and performance failure. Gillberg et al. (1996) found that driving in a simulator for 1.5 hours at night instead of during day significantly increased variability of speed, variability of lane position and subjective weariness. Sagberg (1999) queried randomly chosen drivers (N = 3239) that were recently responsible for driving accidents at the time of the survey. The probability that a crash was weariness-related was five times higher at night (midnight – 6:00 am). Stutts et al. (2003) conducted a case control study with crash data from North Carolina. They compared a) drivers recently involved in crashes related to weariness (N = 467) with b) drivers recently involved in crashes that were not weariness-related (N = 529) and c) non-crash drivers (N = 407). Compared to the other both groups, weariness-crash drivers were nearly twice as likely to work at more than one job and their job involved more frequently non-standard hours. In addition, weariness-crash drivers reported more frequently to have difficulties falling or staying asleep and rated their overall quality of sleep more often as ‘poor’ or ‘fair’. They also stated twice as often to have an inadequate amount of sleep. That said, almost 30 % of weariness-crash drivers reported getting six or fewer hours of sleep the night before their crash, for non-weariness crash drivers, this was the case for less than 10 %. Working the night shift increased the odds of having a weariness-related compared to a weariness-independent crash by almost six times. Compared to 8 hours of sleep the night before the crash, sleeping only for 6 – 7 hours increased the odds ratio that the crash was weariness-related for 2.58. With further reduced sleep, the odds ratio increased even more steeply. The long list of findings is supported by the fact, that weariness-related vehicle accidents peak around 02:00 – 06:00 h and 14:00 – 16:00 h (Garbarino et al., 2001; J. Horne & Reyner, 2001).

Additional studies found a relationship between weariness crashes and job situation. For example Barger et al. (2005) queried 2737 interns of U.S. medical schools. They compared the odds for having a motor crash after a regular work shift with an extended work shift longer than 24h. In comparison, the odds ratio for reporting a motor vehicle crash was 2.3 and for a near miss incident 5.9 with the long work shift. These findings are especially alarming given the fact, that long-haul truckers reported they only sleep for 4.78 hours a day compared to a self-reported ideal amount of sleep of 7.1 hours in the study by Mitler et al. (1997). In addition, it is expected that working times outside the circadian rhythm will increase in the future (Rajaratnam & Arendt, 2001).

However, also job-independent occasions exist that lead to increased sleepiness behind the wheel. Philip et al. (1996) interviewed automobile drivers (N = 567) traveling on summer vacations. The drivers were queried at a roadside rest stop in France during day (8:00 am - 8:00 pm). Half of the drivers reported to have a sleep restriction before departure and 10 % had no nocturnal sleep at all. They also found, that drivers younger than 30 years were significantly more acutely sleep deprived.

2.2 Fatigue

Besides sleep related factors, fatigue plays a major role in the development of weariness. Referred to Beirness et al. (2005, p. 6), “fatigue refers to the reluctance to continue a task as a result of physical or mental exertion”. Fatigue generally manifests itself in performance decrements (Pattyn et al., 2018) and as “extreme and persistent tiredness, weakness or exhaustion - mental, physical or both”(Dittner et al., 2004, p. 157). Thus fatigue manifests itself in multiple aspects including a decreased capacity for work, unwillingness to apply effort to the task, perceived reductions in personal efficiency, and subjective discomfort and tiredness (G. Matthews & Desmond, 2002). It has been shown, that driving performance also decreases over time without sleep deprivation, for example, by Oron-Gilad et al. (2008) and Van der Hulst et al. (2001).

Fatigue is multifaceted construct, which is relevant in different scientific fields. Different forms of fatigue exist, which have different causes and consequences. Firstly, *acute fatigue* can be separated from *chronic fatigue* (Shen et al., 2006). Acute fatigue is perceived as a normal protective function of the body. It shows a rapid onset and is of short duration, and usually linked with a single cause. Chronic fatigue in contrast is perceived as abnormal and primarily affects clinically disordered populations. The role of chronic fatigue in transport is outside the scope of this thesis, therefore the following will only consider acute fatigue.

Secondly, a division can be made between physical and mental fatigue, which are also referred to as physiological or psychological fatigue (Shen et al., 2006). Physical fatigue describes the inability of muscles to perform optimally and is of great relevance in exercise science (Budgett, 1998; Meeusen et al., 2006; Meeusen & Roelands, 2018). In driving, however, it is primarily mental fatigue that is of relevance. Therefore, the following parts of this thesis will focus on mental fatigue.

2.2.1 Mental fatigue

As resistance to mental fatigue is also referred to as vigilance (Pattyn et al., 2018), the constructs will be described together in this chapter. Vigilance describes the ability of organisms to stay attentive and alert to stimuli for prolonged time (Warm, 1993). Vigilance has been of interest for some time. During World War II, for example, the degradation of target detection over time in radar surveillance was of specific interest. The central finding of vigilance research is the fact, that detection performance declines over time, which is referred to as vigilance decrement (Warm et al., 2008). Dependent on the task, the performance decreases with different speeds. These decrements can occur quite rapidly as for example described for visual letter detection tasks (Helton et al., 1999, 2007; Rose et al., 2002; Temple et al., 2000). A significant deterioration of performance occurred already after two minutes. Lal & Craig (2001) describe the major symptoms of mental fatigue as a general sensation of weariness, feelings of inhibition and impaired activity. In general, mental fatigue leads to increased error rates (Wascher et al., 2014), reduced productivity (Sievertsen et al., 2016) and increased reaction times (Lim et al., 2010). As fatigue increases with time, inattention in driving especially occurs on prolonged journeys with long distance (Gimeno et al., 2006). It is, however, important to emphasize that the symptoms of mental fatigue negatively affect performance already before the operator falls asleep (Patel et al., 2011).

For completeness, it is mentioned that mental fatigue is partially further subcategorized into *sleep-related* and *task-related fatigue* (May & Baldwin, 2009)[1]. In such cases, sleep-related fatigue is equivalent to sleepiness. In this thesis however, fatigue and sleepiness are treated as separate concepts, in line with other authors (Beirness et al., 2005; Pattyn et al., 2018; Philip et al., 2005). For this reason, the term sleepiness is used in this thesis.

2.2.2 Passive driver fatigue

May & Baldwin (2009) divide mental fatigue[1] in the driving context into *active* and *passive driver fatigue*. Although the causes of active and passive fatigue are different, they both lead to vigilance decrement. Active driver fatigue is the result of excessive workload due to high levels of task complexity, which can be for example found in high traffic situations. The term passive driver fatigue is used to describe the reduction in attention during very simple driving tasks. Besides underload, monotony is listed as a cause of this phenomenon. Larue et al. (2009) describe monotony as a task characteristic, related to highly repetitive, constant or infrequent stimuli.

For most operators, driving is an overlearned skill, that does not require their full attentional capacity (Beirness et al., 2005). Consequently, many driving situations are routine, monotonous and even boring. This is especially the case on long motorway journeys, journeys at night, in low traffic, roads with few curves, persistent noise levels and monotonous surroundings, such as noise barriers and deserts (Beirness et al., 2005; Farahmand & Boroujerdian, 2018; Larue et al., 2011). In these situations the underdemanding task is accompanied by a monotonous surrounding which only provides low visual, motor or cognitive stimuli which further promotes vigilance decrement (Larue et al., 2011, 2009). Consequently, the driving task is mainly reduced to lane keeping. In comparison, only few vehicle accidents happen due to weariness on urban roads as the driving conditions are more stimulating

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[1] The authors do not explicitly state if they refer to mental or physical fatigue. However, as they describe fatigue in the driving context, it is assumed that the classification refers to mental fatigue.

(J. Horne & Reyner, 2001). Professional drivers such as truck and bus drivers particularly often face monotonous driving situations (Williamson et al., 1996).

In advanced stages of passive driver fatigue, ‘highway hypnosis’ can occur (Cerezuela et al., 2004; Wertheim, 1978). During the state of highway hypnosis, the driver remains in a normal sitting position and often keeps the eyes opened. After regaining attention, the driver nevertheless hardly remembers anything about the way travelled.

Numerous studies reflect the negative effect of passive driver fatigue. Thiffault & Bergeron (2003) showed in a simulator study that alertness, measured with frequency of steering wheel movements, was lowered due to a repetitive and monotonous road environment in comparison to a road environment that contained disparate visual elements. The findings are supported by Farahmand & Boroujerdian (2018) that examined the impact of low, moderate and high levels of road geometry variability in a simulated ride over 45 minutes. Decreasing road variability led to a significantly worse lane keeping behavior. Another driving simulator study investigating the influence of road design on vigilance was conducted by Larue et al. (2011). Alertness decrements in the 40 minute ride were affected by: time-on-task, road design variability, roadside variability and subject’s sensation seeking level; but they were unaffected by: driver’s extroversion level, gender, testing time, age, driving experience, amount of sleep and caffeine consumption. Larue et al. (2011, p. 2043) emphasize, that “this monotony induced impairment should not be mistaken for driver fatigue due to sleep deprivation or circadian rhythm”. Saxby et al. (2007) compared a control condition with a passive and active fatigue condition. In the active condition, additional wind gusts required an increased number of steering and acceleration changes. The passive condition was fully autonomous, the subjects only had to monitor a screen and press a turn signal in case of ‘automation failure’. The authors found that task engagement was lowest in the passive condition, followed by the control and active condition. In order to investigate the impact of lowered task engagement on driving parameters, another study was conducted with equivalent conditions (Saxby et al., 2008). In this study, each condition was followed by a 4-minute drive. At minute 2:30, a van pulled out in front of the participants’ vehicle, forcing a breaking maneuver. Although better lane keeping was obtained following the passive condition, the active condition showed significantly faster braking und steering responses to the van. As a result, significantly fewer collisions happened in the active compared to the passive condition. The authors conclude from these findings, that passive fatigue led to a higher overall impairment. The results of both studies are discussed in detail in Saxby et al. (2013).

The previous findings from simulator studies were also found in real driving. Cerezuela et al. (2004) compared a ride on the motorway with one on a conventional road over approximately 90 km and 45 minutes. At the beginning of the drive, fatigue (measured with electroencephalography) was higher on the conventional road. At the end of the ride, in contrast, fatigue was higher on the motorway. The findings indicate, that sustained attention was lower on the conventional road in comparison to the motorway.

2.2.3 Theories on the influence of monotony and underload on mental fatigue

From Chapter 2.2.2, it is evident that both monotony and low task demand are seen as causative factors for passive driver fatigue. However, up to date, the exact contribution of monotony and task demand on mental fatige has not clearly explained. Consequently, it is also not entirely clear how the two factors influence the development of passive driver fatigue. The explanation is further complicated by the fact, that many factors associated with mental fatigue do not have a clear definition themselves. This is especially the case for the terms task demand, task complexity and task difficulty, as they have a central role in the explanation of mental fatigue. Despite these difficulties, this chapter provides an overview of relevant theories and models that discuss montony and underload in the development of mental fatigue. Afterwards, an attempt will be made to merge the various aspects of the models and theories into a new model of mental fatigue. This general model of mental fatigue should, in turn, help to explain the potential influence of monotony and task complexity on passive driver fatigue. However, it is important to mention, that the model does not claim to provide an absolute or even exhaustive explanation of mental fatigue. This would require studies for verification and would go beyond the scope of the present thesis.

In Chapter 2.2.3.1 the central terms *workload*, *task complexity*, *task difficulty* and *task demand* are defined. On this basis, existing theories and models are presented in Chapter 2.2.3.2. Afterwards, the common model is presented Chapter 2.2.3.3.

2.2.3.1 Terms

In everyday speech, the term *workload* is used interchangeably with task demand, task load or the volume of work. Although the term is occasionally used in this context in the scientific literature as well, there is good consensus that workload actually describes a different construct. Hart & Staveland (1988) assume that workload is a subjectively experienced and hypothetical construct that describes the expenses of a human operator in order to achieve a certain level of performance in a task. That also includes, that the definition of workload is human-centered rather than task-centered. Correspondingly, workload is not an inherent property but it is the sum and interaction between the requirements of a task, the circumstances under which it is performed and the skills, behaviors and perception of the operator. In general, workload includes mental as well as physical aspects. Since driving requires almost exclusively mental resources (de Waard, 1996; Haring et al., 2012), mental workload is most relevant in this task. The general description of workload is applicable to mental workload. Analogous to the general definition of workload, the *effort* being expended for a task is considered by many to be one of the most important components of (if not equal to) mental workload (de Waard, 1996).

According to de Waard (1996), *task complexity* has to be separated from *task difficulty*, which is in line with P. Liu & Li (2012). De Waard (1996) describes task complexity as the objective property of the task, related to the demand on computational processes. Therefore, he characterizes task complexity as independent from the operator. In contrast, he describes task difficulty as the amount of the individual's resources that are required for task performance. This definition is in line with P. Liu & Li (2012) who add, that similarities between task complexity and task difficulty exist, but they are neither independent nor equivalent. They describe task complexity as the objective characteristics of the task, whereas task difficulty includes the interaction between task, task performer and context characteristics.

De Waard (1996) makes a further distinction between task complexity and *task demand*. He describes task demand as the goal that has to be reached. Accordingly, task demand is superordinated to task complexity. The goal settings define task demand and task complexity then describes the underlying operating stages necessary to achieve the goal. In contrast, P. Liu & Li (2012) consider task goals as part of task complexity. For simplification, the definition of P. Liu & Li (2012) will be used in this thesis. From the author's point of view, the distinction made by de Waard (1996) is of little relevance for this thesis. Instead, another construct is used in an already difficult separation of terms. Therefore, the terms task demand and task complexity are considered equivalent in the following. Appendix A shows a table that illustrates the various influencing factors of task complexity that are listed by P. Liu & Li (2012). A detailed discussion would go beyond of the scope of this thesis. For this, please refer to the original publication. However, it is important to recognize from Appendix A that task complexity is a very multifaceted construct.

In short, task complexity describes the properties of a task, which also includes the task goal. Task difficulty describes the operator's individual resources necessary to fulfill the task. Workload describes the subjective expenses of the operator during task performance.

Monotony can generally be distinguished into monotony as an objective task characteristic and subjective monotony as a sensation (Melamed et al., 1995; Shirom et al., 1999). Of the articles in Chapter 2.2.3.2 that use the term monotony, only the article by Larue (2010) includes an explicit note that it refers to monotony as a task characteristic. The remaining publications (de Waard, 1996; Mackworth, 1968; Sharpless & Jasper, 1956) however use the term 'monotonous task' which is seen as a strong indicator that they also refer to monotony as an objective task characteristic. Likewise, the new model of mental fatigue, which is described in chapter 2.2.3.3, treats monotony as an objective task characteristic.

2.2.3.2 Current theories

The following subsections will now present important models and theories that discuss monotony and underload in the development of mental fatigue.

Habituation theory

The Habituation theory attributes an important role to monotony in the loss of vigilance. Monotonous situations are characterized by repetitive and predictable stimuli. The theory posits that the repetitiveness leads to a habituation of the sensory responses that normally occur in reaction to stimuli (Larue, 2010). The absent reaction can often be observed in nature. For example Sharpless & Jasper (1956) studied this phenomenon in cats. In a series of experiments, they investigated the activity response of the posterior suprasylvian gyrus to different modulated tones. The repeated playing of tones during sleep of the cats resulted in a disappearance of reaction to the stimuli even for several days. A potential explanation of this phenomenon is given by Mackworth (1968). In the publication it is hypothesized that the brain continuously creates and adapts models of incoming stimuli. From these models, an estimate is drawn into the future. If the actual event now matches the predictions, the neural responses to this event are reduced. Contrarily, if deviations occur, the neural response is maintained. The prediction model includes different parameters; one of them is time of occurrence. This means that habituation occurs faster when similar stimuli are additionally repeated at a regular rate.

Waard's model of mental workload, task performance and complexity

The model of de Waard (1996) explicitly addresses drivers' mental workload. As shown in Figure 2, the model depicts task performance and workload as a function of task complexity[2]. The model consists of four superordinate zones (A - D) with a further subdivision of zone A into zones A1, A2 and A3.

Region A is the area with the best task performance. In A2, the operator can handle the task easily and the level of performance is stable. In A1 and A3, the operator can still hold the level of performance, but with increasing effort. The generated effort in the A1 region is described as *state-related effort*, while the A3 region requires *task-related effort*. The causes for a transition from A2 to A1 can be for example

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[2] In the original publication (de Waard, 1996) uses the term task demand. As previously described, task complexity and demand are synonymously used in this thesis.

monotony or boredom that starts to affect the operator's state and subsequently diminishes his resources. As a result, his capacity is reduced which consequently leads to a larger proportion of the capacity that is required for the same task. As a result, task difficulty increases, which in turn increases mental workload. A transition from region A2 to A3 is the result of increased task complexity. Temporarily, the additional effort to cope with the task can be covered. On the long term however, or if peak loads occur frequently, this can lead to stress and unhealthy situations. Both region D and B describe the transition from stable performance to a decrease in performance. The loss of performance in region D is due to persistent state-related effort, and in region B because of continuing task-related effort or an increase in task complexity. The fourth region C is positioned on the right side of the continuum and represents heavy task overload.

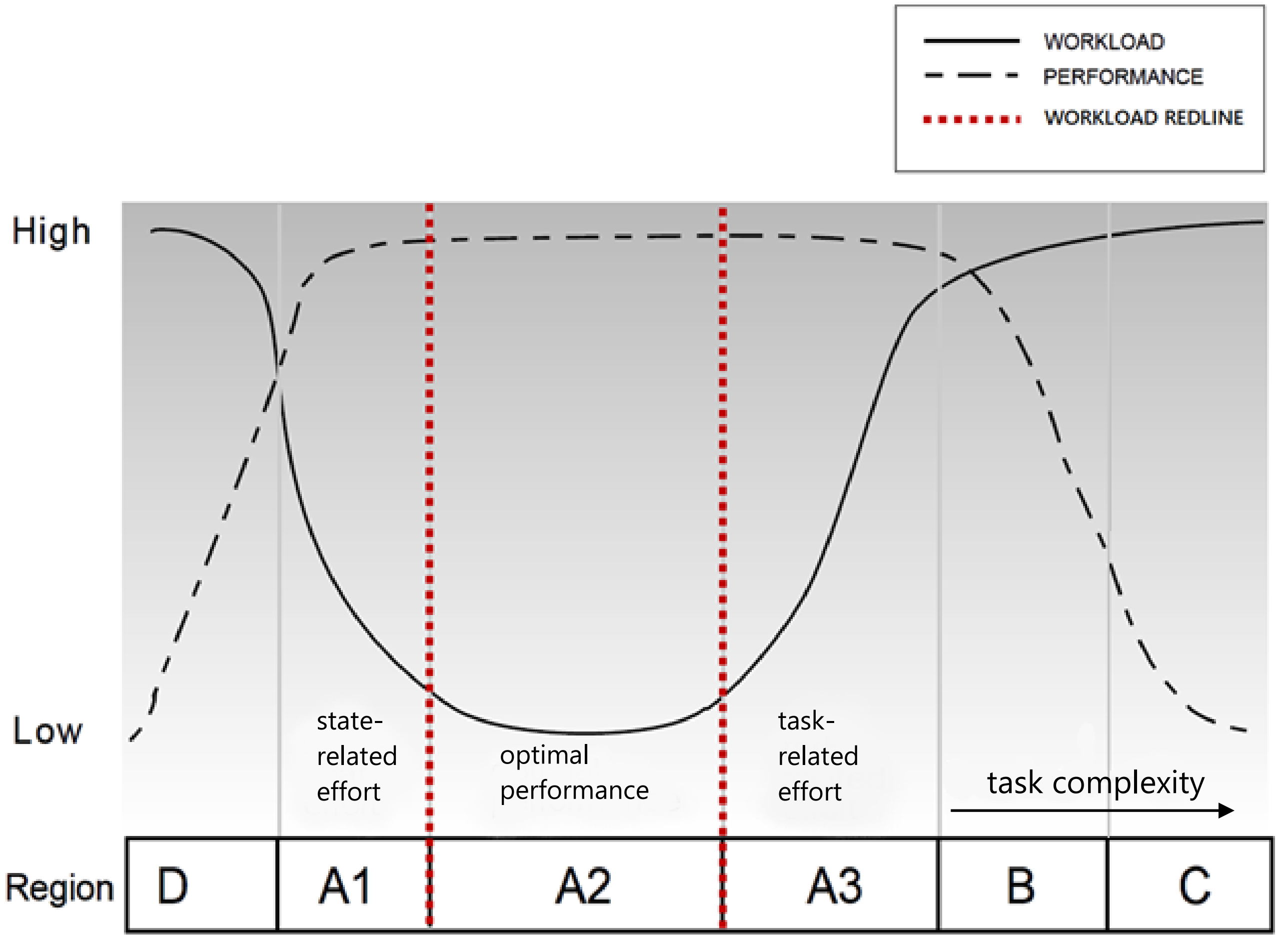

Figure 2: *Modified model of de Waard (1996). In the original model, the x-axis describes task demand. In line with the definition of the terms in this thesis, task demand was replaced by task complexity (see Chapter 2.2.3.1).*

As previously stated in this chapter, workload is person-related, that said, the same task can result in region A3 for one individual and in A2 for another, for example. The inverted U-shape of the model creates associations with the *Yerkes-Dodson law*. The law was formulated based on a paper (Yerkes & Dodson, 1908) that describes the relationship between stimulus strength and habit-formation in mice. In short, the paper states that the stimulus strength should be neither too high nor too low to optimize habit formation. Later the law has been used to describe various relationships, especially between arousal level and performance. However, the more or less unlimited extension of the model to various psychological phenomena is also viewed critically, since studies for verification are often lacking (Teigen, 1994). This is accompanied by the problem, that until today no consensus exists on what exactly constitutes arousal (R. A. Cohen, 2018).

However, the model is supported by the *Malleable attentional resources theory* which is postulated by Young & Stanton (2002). The theory posits, that the size of the resource pool is temporarily diminished in the case of underutilization. Consequently, the attentional capacity is temporarily diminished. If the resources have now lessened due to low demand, a sudden increase in task demand cannot be tolerated, even if it is within the ordinary capacity of the operator.

Attentional resource theory

An alternative explanation for vigilance decrement in repetitive tasks is given by the *Attentional resource theory* (Warm et al., 2008). The theory posits that the loss of performance is due to a depletion of resources that are necessary to maintain attention. In agreement with the model by de Waard (1996), Warm et al. (2008) conclude that repetitive vigilance tasks are characterized by high workload which increases linearly over time. A central contrast is, however, that Warm et al. (2008) do not assume that monotonous tasks are necessarily characterized by low requirements. Instead, vigilance tasks also require attentional resources whose availability decreases over time. The authors justify this hypothesis by the fact, that performance decrement occurs faster in repetitive vigilance tasks with higher task complexity. Faster decrement in more complex tasks occurs for example, when comparing vigilance tasks that require simultaneous or successive target discrimination (Warm et al., 2008). In the easier simultaneous-discrimination tasks, the stimulus itself contains all the information to distinguish whether it is a target stimulus. In the more complex successive-discrimination tasks, the stimulus must be compared with a nonsignal reference for classification, which must be stored in the working memory (Parasuraman & Mouloua, 1987). As an example for a simultaneous-discrimination task G. Matthews et al. (1993) mention the detection of a specified digit in a sequence of digits such as in Rosvold et al. (1956). A successive-discrimination task, in contrast, would require the detection of a sequence of three consecutive odd digits, for which the first two have to be stored in the working memory (Bakan, 1959).

The finding that repetitive vigilance tasks also require attentional resources can additionally be supported with objective measurements. In studies with Transcranial Doppler Sonography, cerebral blood flow velocity was measured during vigilance tasks (e.g. Warm et al., 2009). The vigilance decrement was accompanied by a temporal decline in blood flow velocity especially in the right hemisphere

2.2.3.3 New model of mental fatigue

This Chapter proposes a new model, which attempts to combine the aspects of the models and theories from Chapter 2.3.3.2 into one common model of mental fatigue. In all preceding approaches, there is agreement that repetitiveness of stimuli promotes vigilance decrement. Furthermore, with exception of the *Habituation theory*, all approaches describe, that performance decreases over time due to a depletion of attentional capacities. The main contradiction is, that the Model by de Waard (1996) and the *Malleable attentional resources theory* assume that repetitive tasks limit the operator’s capacity pool through monotony or boredom, whereas the *Attentional resource theory* assumes that such tasks are indeed demanding and expend the operator’s capacities.

From the author’s point of view, it is important to consider two aspects. Firstly, vigilance tasks with low target stimuli, such as simple driving tasks, require few and mostly simple reactions. Nevertheless, the driver must react quickly in dangerous situations. Therefore, a permanent scanning of the environment is crucial. The continuous readiness for action supports the hypothesis that vigilance tasks indeed require attentional resources. The second aspect to consider is that in practice, tasks with low complexity are often accompanied by high monotony and vice versa. For example, when comparing driving in the city and on the highway, one should be aware that both task complexity and monotony change. Consequently, just because mental fatigue develops in tasks with low complexity, one should be cautious to determine this as the causative factor. Therefore, from the author's point of view, a clear differentiation of monotony from task complexity is necessary.

In accordance with de Waard (1996), the new model assumes that high workload leads to mental fatigue and thus a rapid decline in performance. The model treats task complexity and monotony as separate constructs. In the three-dimensional model (see Figure 3), workload is plotted on the vertical axis whereas monotony and task complexity are represented on the horizontal axis. This means, workload can separately increase due to high task complexity or monotony. However, the simultaneous elevation of both constructs leads to an even steeper increase of workload. At this point one should remember that workload

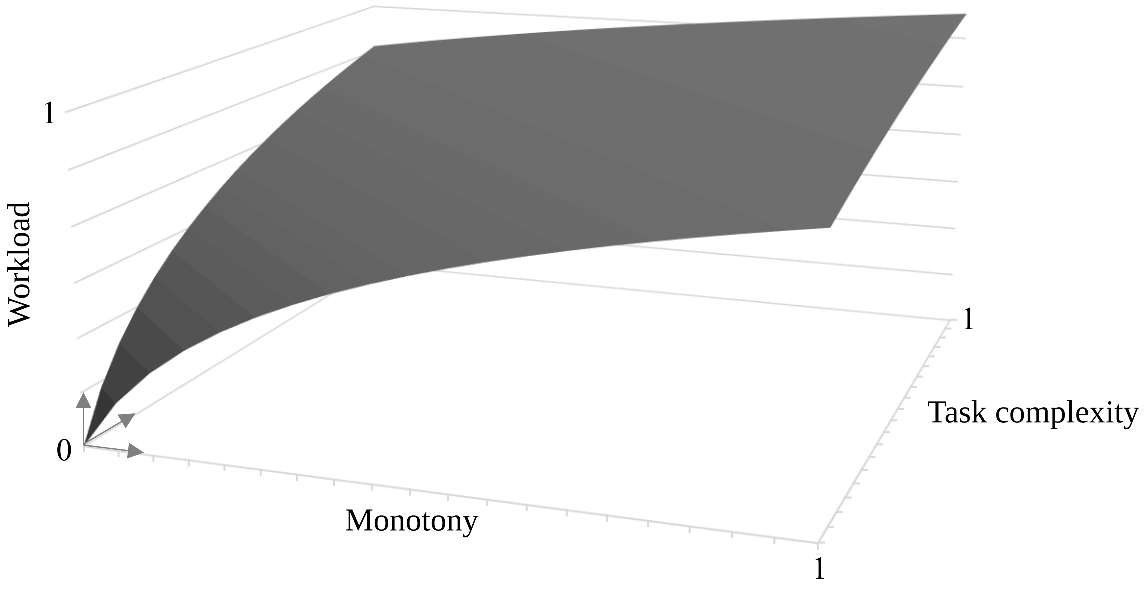

Figure 3: *Illustration of the new three-dimensional model that depicts workload as a function of monotony and task complexity. The values are normalized such that a value of 1 indicates maximum monotony, workload and task complexity. It can be assumed that the value 0 is theoretical and that tasks in practice always have a minimum level of task complexity and monotony and thus also workload, which is thus above 0.*

is person related. Consequently, the shape of the surface is not the same for every operator. The individual shape depends on how the operator can cope with monotony and task complexity.

With current models, it is difficult to explain that increasing task complexity both improves and deteriorates task performance. Saxby et al. (2007) found that driving performance on curvy roads and with wind gusts was better than in semi-autonomous driving, despite the higher task complexity. Warm et al. (2008) on the other hand reported that more difficult successive-discrimination tasks lead to a faster performance decrement than easier simultaneous-discrimination tasks. Now, according to de Waard (1996) one might argue that the operator was pushed from the underload to the optimal state in the first example, and from the optimal to the overload state in the second example. However, since a number of experiments showed that more difficult successive-discrimation tasks lead to faster performance decrement (Warm et al., 2008), this would have been the case in each of these experiments. This assumption is a rather unsatisfactory.

The new model that is proposed in this chapter might help to explain this contradiction. For successive-discrimination tasks, the additional demand on working memory leads to a higher task complexity, but the monotony is (more or less) maintained because the structure of the task remains largely the same. In the second case on the other hand, it is likely, that the monotony decreases with increasing task complexity, since the more difficult task includes additional elements. In this case, a lower overall workload might be the result. Although the wind gusts lead to an increased task complexity and consequently higher workload, this effect might be overcompensated by the reduction of monotony.

Finally, this resolves the major contradiction between the theories. Task complexity can negatively affect the performance through higher consumption of resources, while monotony further aggravates the performance decline through a reduction of the available resource pool. This means that both monotony and task complexity should be kept as low as possible to reduce mental fatigue and optimize driving performance.

2.2.4 The influence of automation on passive driver fatigue

For warranting safety, health, comfort and long-term productive efficiency of the user, a task should be neither overloading nor monotonous. In this context, the risks of overload have long been recognized. Increasingly, the dangers of tasks with high monotony are also gaining in awareness, particularly as tasks become increasingly automated (Rubio et al., 2004). While in the past, deactivating situations were mainly caused by monotonous highway driving for a long duration, these situations might grow with more functions taken over by technology. While this technology can prevent the driver from excessive demand in high traffic situations, it might under certain circumstances also lead to the opposite effect of monotony (de Waard, 1996). In this context, the stage of semi-autonomous driving is of particular importance. It will take some time before road vehicles can drive fully autonomously. Until then, the driver is still responsible for monitoring the vehicle and must take over the controls himself occasionally and within short time. Assistive devices such as cruise control reduce the driving task on highways to a lane-keeping task (Larue et al., 2009). As a result, semi-autonomous driving increases the monotony of the task, but the driver must still remain attentive and take responsibility for the vehicle (Casner et al., 2016; Walch et al., 2017).

2.3 Weariness as a result of mental fatigue and sleepiness

The findings of Chapter 2.1 and 2.2 are incorporated into a model of weariness, which is shown in Figure 4. In summary, both sleepiness and fatigue contribute to weariness, which ultimately leads to driving errors and a bad driver condition. This assumption is line with Beirness et al. (2005) who state that fatigue might be worsened if driving is undertaken under greater sleepiness.

A distinction is made between active and passive driver fatigue. The former type of fatigue is caused by task overload and the latter by monotony. However, in the model proposed in this thesis, both forms of fatigue can occur simultaneously. The worst case of a task with high complexity and monotony would lead to both active and passive fatigue adding up to high overall fatigue.

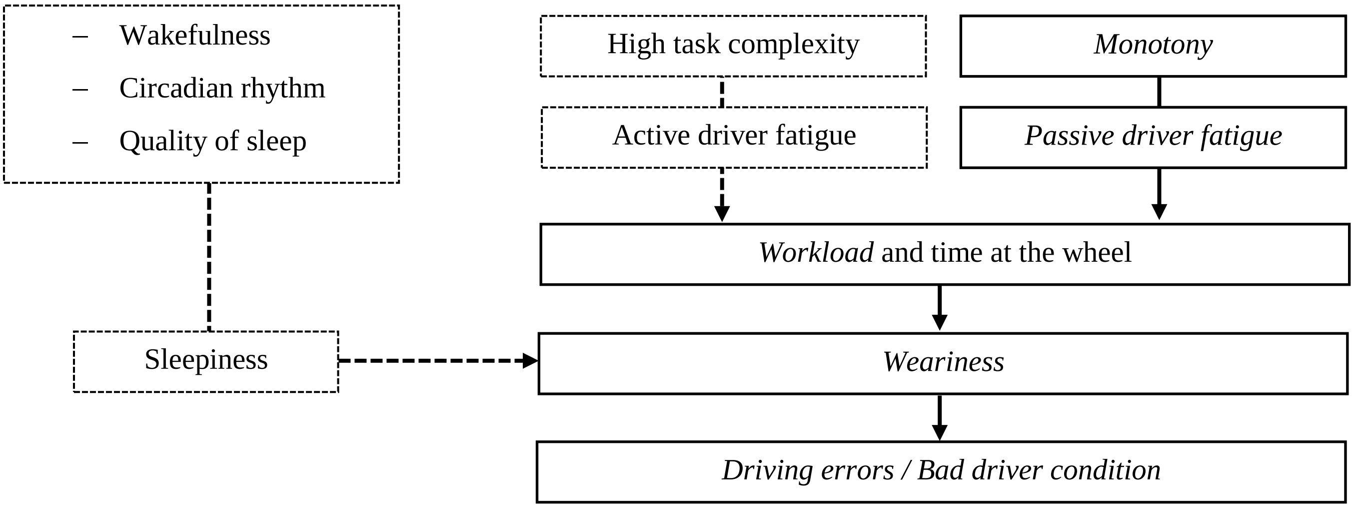

Figure 4: *Model of weariness that is based on the literature discussed in Chapter 2.1 and 2.2. Factors that shall be improved by the interactive seating system are written in italics and outlined with solid lines.*

Both sleepiness and fatigue contribute to weariness, moreover, there is evidence that in practice, the two often go hand in hand. For example Philip et al. (1999) found in their study, that long distance driving was correlated with sleep deprivation. The authors queried 2007 drivers. Using stepwise multiple regression analysis including 14 variables, they found, that duration of the drive was the most important determinant for sleep dept. This finding is supported by Kaneko & Jovanis (1992) who analyzed driving patterns over 7 days from over 1000 truck drivers. Besides the hours driven on the day, also driving in the early and late morning (e.g. midnight to 10 am) had a significant effect on accident risk.

Sleepiness and fatigue might also interact with each other. For example Philip et al. (2003) investigated the impact of sleep duration on reaction time in highway driving over 1000 km. The subjects (N = 10) drove the route once with usual sleep (8.5 hrs) and once with restricted sleep (2 hrs). In this study, reaction time only significantly increased over driving time in the condition with sleep restriction. From these findings, it can be concluded, that sleepiness aggravated the consequences of fatigue. It should however be kept in mind that with driving duration also the sleep deficit and therefore sleepiness might have increased.

2.4 Measurement methods of passive driver fatigue

This chapter will give an overview of frequently used methods to capture passive driver fatigue. For an extensive overview, please refer to Bier et al. (2018), C. C. Liu et al. (2009), Sahayadhas et al. (2012) and Sparrow et al. (2019). Since sleepiness and passive driver fatigue lead to the same consequences in the driving context, the same methods are used for their measurement. That is why the listed methods are sometimes also referred to as sleepiness or drowsiness measures in the literature. It also explains, why questionnaires that were originally developed to assess sleepiness can measure passive driver fatigue (Bier et al., 2018). Gimeno et al. (2006) generally divide the methods to capture passive driver fatigue into: (1) questionnaires or drivers' reports, (2) tracking of task performance and (3) recording of physical and psychophysiological activity.

Since passive driver fatigue is induced by monotony, there are specific aspects to consider when selecting appropriate measurement methods for studies. In order to maintain the monotony, the measurement should be automatic, unobtrusive and not interfere with the main task (Gimeno et al., 2006). This aspect is especially important when collecting questionnaires. During a 4-hour drive, E. A. Schmidt et al. (2011) queried passive driver fatigue with a questionnaire (Karolinska sleepiness scale) every 20 minutes. They observed, that the short verbal assessment had an awakening effect, even though this effect only persisted for up to two minutes. That is why it is preferably to use questionnaires only before and after the drive. In addition, questionnaires cannot deliver continuous information, as there are certain periods between the survey intervals. Thus, questionnaires cannot provide information about real time fluctuations of passive driver fatigue (Larue et al., 2009). That is why Bier et al. (2018) suggest using additional physiological measurements to continuously monitor the subject at high resolution. The measurements can be started before the drive and permanently record the relevant data. This advantage also applies to the methods that capture task performance. However, since only questionnaires directly capture the subjective perception of fatigue, they should complement performance and physiological measurements.

In the following, commonly used measurement methods including questionnaires as well as performance and physiological measurements will be listed.

2.4.1 Questionnaires

Three questionnaires for assessing passive driver fatigue are listed below. Among these questionnaires the Karolinska sleepiness scale is most frequently used (C. C. Liu et al., 2009), followed by the Stanford Sleepiness Scale. The Fatigue severity scale is only rarely used. Sleepiness scales can be used to capture fatigue since subjects cannot differentiate between symtoms of fatigue and sleepiness (Bier et al., 2018).

- The *Karolinksa sleepiness scale* is a Likert scale that ranges from (1) ‘extremely alert’ – (9) ‘very sleepy, great effort to keep awake, fighting sleep’ (Miley et al., 2016). The questionnaire was used in multiple studies (Åkerstedt et al., 2005; Buendia et al., 2019; J. A. Horne & Baulk, 2004; Ingre et al., 2006; Mets et al., 2011; Philip et al., 2005).
- The *Stanford sleepiness scale* is a Likert scale that ranges from (1) ‘Feeling active, vital, alert or wide awake’ – (7) ‘No longer fighting sleep, sleep onset soon; having dream-like thoughts’ (Hoddes et al., 1973). The scale is for example used in Arnedt et al. (2000), de Valck & Cluydts (2001) and Ting et al. (2008).
- The *Fatigue severity scale* includes nine items. Each one can be rated on a scale from (1) ‘strongly disagree’ to (7) ‘strongly agree’. Bener et al. (2017) used this scale to capture general sensations of fatigue. However, the scale originates in the clinical field, and is rather used to measure the effects of diseases on driving behavior, e.g. depressions (Tsoutsi et al., 2019).

2.4.2 Task performance

Inferences about passive driver fatigue based on task performance are usually drawn from the driving task itself, with lane keeping ability being most frequently used. However, in some cases passive driver fatigue is also assessed by a secondary task. All task performance measures are expected to increase with increasing PDF.

- The *standard deviation of lateral position* describes the variance of the vehicle’s path. As fatigue increases, the lane keeping becomes less accurate which increases the variance of the path (Åkerstedt et al., 2005; Arnedt et al., 2001; Forsman et al., 2013; Gershon et al., 2009; Ingre et al., 2006; Lenné et al., 1997; Merat & Jamson, 2013; Mets et al., 2011; Moller et al., 2006; Ting et al., 2008).
- The *number of lane crossings* describes the frequency with which the vehicle exceeds the lane markings. A distinction can be made whether a single wheel, multiple wheels, the entire vehicle or its center has left the lane (Åkerstedt et al., 2005; Moller et al., 2006; Verwey & Zaidel, 1999, 2000). In addition, it can be distinguished, whether only the outside lines of the lane or even the road edge has been crossed (Arnedt et al., 2001; de Valck & Cluydts, 2001; Fairclough & Graham, 1999; Philip et al., 2005; Ting et al., 2008; Verwey & Zaidel, 1999, 2000).
- The *number of accidents* can be calculated, for example, from collisions with other vehicles (de Valck & Cluydts, 2001; Fairclough & Graham, 1999; Ting et al., 2008).
- The *standard deviation of steering angle* is influenced by the operator’s steering behavior. With increasing fatigue, the steering becomes less precise which leads to a higher variability of the steering angle (Forsman et al., 2013; Gershon et al., 2009; Oron-Gilad et al., 2008)
- The *standard deviation of velocity* reflects the ability to keep the vehicle at constant speed. This ability decreases with fatigue which in turn increases the variance of velocity (Gershon et al., 2009; Lenné et al., 1997; Mets et al., 2011; Ting et al., 2008).
- The *deviation from speed limits* increases with fatigue, as the observation of speed limits becomes less precise. The absolute deviation as well as its variability can be considered (Arnedt et al., 2001; de Valck & Cluydts, 2001; Moller et al., 2006).
- The *reaction time* can be directly linked to the driving situation, such as reactions to wind gusts (Moller et al., 2006) or pedestrians (Steinberger et al., 2017). However, it can also be detected through

additional tasks while driving, for example by a response to visual stimuli such as light signs (Philip et al., 2005; Ting et al., 2008).

2.4.3 Eye data

Passive driver fatigue affects eye parameters which can be measured with eye tracking systems.

- As the name indicates, *eyelid distance* is calculated via the distance between the eyelids (Larue et al., 2011; Sagberg et al., 2004). With increasing passive driver fatigue, the distance between the eyelids decreases.
- *PERCLOS* is calculated as the percentage of time the eyes are closed (Merat & Jamson, 2013). Therefore, a state has to be defined at which the eyes are classified as being closed. For this, different thresholds can be found in the literature: 60, 70, 75, and 80 % (Junaedi & Akbar, 2018; Merat & Jamson, 2013). From those, 80 % seems to be most widely accepted. However, some authors apply those thresholds to the proportion of the pupil that is covered by the eyelid in vertical direction (Hayami et al., 2002), other authors calculate it based on the estimation of the iris (Junaedi & Akbar, 2018). PERCLOS increases with increasing passive driver fatigue (Hayami et al., 2002).
- *Blink frequency* describes the number of blinks, given in a certain time interval. With increasing passive driver fatigue, blink frequency is expected to increase (Körber et al., 2015; Larue et al., 2011)
- *Blink duration* is expected to increase with increasing passive driver fatigue as well (Åkerstedt et al., 2005; Ingre et al., 2006; Körber et al., 2015).

2.4.4 Vital data

In addition to eye tracking data, vital data is used as a physiological measure to gather information about passive driver fatigue.

- *Heart rate* describes the number of heartbeats in a given time interval (Brookhuis & de Waard, 2010). Heart rate is expected to decrease with increasing fatigue (Buendia et al., 2019; Jahn et al., 2005; Larue et al., 2011; Liang et al., 2009).

- *Heart rate variability* describes the variation of the time intervals between consecutive heartbeats (Brookhuis & de Waard, 2010). This parameter is expected to increase with increasing PDF (Buendia et al., 2019; Liang et al., 2009).
- *Skin conductance* is a parameter of electrodermal activity. This parameter gives information about the activity of the eccrine sweat glands which is captured through the application of external voltage on the skin (S. Schmidt & Walach, 2000). As the sweat glands on the skin are innervated by the sympathetic nervous system only, it is a good indicator of arousal level due to external sensory and cognitive stimuli (Jang et al., 2015). In measuring skin conductance, a distinction can be made between the phasic and tonic principle. The tonic value describes the activity over longer periods and reflects the overall arousal of a person. It is obtained by measuring the total amount of skin conductance and is referred to as skin conductance level. The phasic value describes the change of the skin conductance within a short time period as a reaction toward discrete stimuli. Passive driver fatigue is commonly measured with *skin conductance level*, which is expected to decrease with increasing fatigue (Larue et al., 2011). Besides skin conductance, skin resistance is frequently reported to give information about electrodermal variations. Skin resistance is the inverse function of skin conductance (Collet et al., 2009).

2.4.5 Brain activity

The assessment of passive driver fatigue through neuronal activities is usually measured with electroencephalography. The activity in certain frequency bands gives information about different levels of fatigue (Sahayadhas et al., 2012; Simon et al., 2011). Sahayadhas et al. (2012) describe four activity levels depending on the frequency bands:

- Delta band (0.5 – 4 Hz): sleep activity
- Theta band (4 – 8 Hz): drowsiness
- Alpha band (8 – 13 Hz): relaxation, creativity
- Beta band (13 – 25 Hz): alertness

The analysis can either consider single frequency bands (Lal & Craig, 2001) or calculate quotients of multiple frequency bands. For example Larue et al. (2011) and Rogé et al. (2009) calculated the following quotient for the assessment of alertness: (Thetha + Alpha)/Beta. Besides the frequency itself, certain frequency patterns which are referred to as spindles can also be calculated. Among these, the most prominent is the alpha spindle activity, which increases with enhanced passive driver fatigue (Jellentrup et al., 2011; E. A. Schmidt et al., 2011; Schneider et al., 2021).

2.5 Countermeasures against weariness behind the wheel

Different measures for the prevention of weariness related vehicle accidents exist. These measures can either prevent the driver from becoming fatigued or sleepy, or they can alert the driver or intervene with driving once the driving is impaired (Sagberg et al., 2004).

For the latter, numerous systems in series-production vehicles exist, that give a warning signal if the driver shows signs of weariness. Such systems are for examples lane departure warning systems (Bartels et al., 2015). However, literature indicates, that drivers are generally aware of being fatigued or tired. One example is a simulator study over two hours, which was conducted by Williamson et al. (2014). The authors found, that if subjects rated to fall asleep in the next minutes, the likelihood to crash increased by factor four, to cross the centerline by factor ten. This finding is supported by another simulator study with a duration of 2.5 hours (Van der Hulst et al., 2001). In this study, a significant correlation was found for the self-assessment of performance quality and an increase of subjective sleepiness, fatigue and variability of lane position. Both studies indicate that weariness at the wheel is recognized but ignored, or at least its consequences are underestimated.

Therefore, it seems useful, to prevent the occurrence of weariness in the first place. For this aim, different approaches already exist, that will be listed in the following. According to MacLean et al. (2003) these approaches can be divided into those that reduce the physiological need for sleep and those which attempt to activate the driver.

2.5.1 Countermeasures aiming to reduce sleepiness

MacLean et al. (2003) state that one of the best countermeasures for weariness is appropriate rest and the consideration of the circadian rhythm both before and during the drive. This opinion is also shared by the participants in a study by Vanlaar et al. (2008). The respondents were asked to rate measures against weariness regarding their effectiveness. Most frequently mentioned was ‘ask passenger to drive’, followed by ‘stop to nap or sleep’ and just ‘stop’. However, relatively ineffective actions such as opening the window or playing music were mentioned as countermeasures used in practice, whereas taking a rest was the least popular. Accordingly, the participants considered taking a break to be an effective countermeasure against weariness, but they do not use it. This discrepancy is also reflected in the study by Arnold et al. (1997). The authors queried 638 truck drivers in an Australian state without restricted driving hours. When asked what strategies the drivers use to counteract fatigue, 81.7 % answered they would pull over and sleep. At the same time, 11 % of the drivers worked more than 90 hours in the previous week, 51 % exceeded 14 hours of working[3] on the day of the interview, and 12 % reported having had less than 4 hours of sleep on one or more working days in the preceding week of the interview. Only 10 % of the drivers stated weariness to be a problem they always or often experience. On the other hand, 39 % of the drivers thought that other truck drivers often or always experience weariness. The lack of willingness to take breaks is supported by a case control study by Stutts et al. (2003) in which less than 12 % of the drivers stated that they would stop driving and only 8 % would stop for a nap.

Additional to the lack of practice, taking a break or nap does not always prove to be effective. In a study by Rogé et al. (2009), a 30-minute nap showed no effect on alertness (measured with electroencephalography) and the detection of motorcycles and signals. Another example can be found in the publication of Gillberg et al. (1996) in which a simulated truck driving task over 1.5 h was conducted

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[3] Working hours included driving plus other non-driving work.

at night. Neither a rest nor a nap showed any effect on driving parameters, subjective weariness, reaction time and electroencephalographic recordings.

Another approach to reduce sleepiness is the consumption of caffeine. Brice & Smith (2001) observed in a 1 hr simulated drive, that 3 mg/kg caffeine led to a higher subjective alertness, improved steering variability and reduced number of lane crossings. Less lane drifting after coffee consumption was also found in a study with partial sleep deprivation by de Valck & Cluydts (2001). In addition, the authors found a smaller speed deviation, accident liability and subjective sleepiness. In a study by Philip et al. (2006) caffeine intake resulted in significantly less lane crossings in a real world driving task for 1.5 hours at night. Reyner & Horne (2002) tested the efficacy of a functional energy drink after sleep deprivation. Subjective fatigue was significantly reduced and line crossings occurred less frequently at least for the first 90 minutes of the ride. The previous findings are supported by Mets et al. (2011). In comparison to a decaffeinated placebo, the caffeinated energy drink significantly improved standard deviation of lane position, standard deviation of speed, mental effort and subjective sleepiness. However, despite the benefits of caffeine for the reduction of sleepiness, it should be remembered that the consumption can lead to abuse and addiction (Cappelletti et al., 2015).

Another approach to reduce sleepiness is the application of blue light. For example Taillard et al. (2012) compared a placebo, caffeine intake and blue light exposure during real driving for 4:15 hours. In comparison to the placebo, less inappropriate line crossings were found for both caffeine and blue light. However, Souman et al. (2018) reviewed 68 studies that investigated the alerting effects of increased color temperature of white light (containing more power in the short, blue appearing wavelengths). In the reviewed studies, the alerting effect of blue light was only partially confirmed; therefore, the efficacy is not completely clear.

2.5.2 Countermeasures aiming to reduce monotony

Besides the reduction of the physiological need for sleep, another approach to reduce weariness is the modification of the driving task to be less fatiguing. Since passive driver fatigue is caused by monotony, it seems promising to increase the variability of the task. As shown in Table 1, this has been previously done in the literature in three ways. First, the situation in which the task is performed can be manipulated with additional task-independent stimuli. Secondly, the task itself can be manipulated. This can be done either by setting new stimuli which relate to the task or by the execution of a secondary task (Bier et al., 2019; Verwey & Zaidel, 1999).

Table 1*: List of countermeasures against passive driver fatigue.*

a) Additional task-independent stimuli	
Thermal stimuli	E. Schmidt et al. (2017), E. Schmidt & Bullinger (2019)
Motion seating	S. Lee et al. (2020)
Mobilization seat	Schneider et al. (2021)
b) Additional task-dependent stimuli	
Variation of driving environment	Merat & Jamson (2013)
Games related to driving	Bier et al. (2019), Steinberger et al. (2017)
c) Secondary tasks	
Phone calls	Neubauer et al. (2014)
Quiz games while driving	Gershon et al. (2009), Neubauer et al. (2014), Oron-Gilad et al. (2008)
Mental games while driving	(Verwey & Zaidel, 1999)

2.5.2.1 Additional task-independent stimuli

Several studies investigated the alerting effects of task-independent stimuli, either in tactile or thermal form. The application of tactile stimuli was realized with seating systems. Schneider et al. (2021) compared a seat-integrated stimulation system with a placebo condition. The seat mobilizes the passenger with inflatable air bladders. The system was tested in a standardized vigilance truck-driving task at a limited speed of 35 kph. Compared to the placebo condition, the seating system reduced the loss of attention, assessed via electroencephalographic alpha spindle rate. However, no significant influence on reaction time and subjectively perceived fatigue was found. Another study investigated the alerting effects of a motion seating system (S. Lee et al., 2020). The system activated coordinated motions of the backrest recline, cushion tilt, and lumbar support. The use led to a significant reduction of the standard deviation of velocity, PERCLOS and subjective fatigue. However, no influence on the steering wheel rate was found.

In the literature, additional thermal stimuli were applied with facial cooling. In the study of E. Schmidt & Bullinger (2019) the circulation of cold air on the subjects led to a significant reduction of subjective fatigue and increase of pupil size, which is associated with sympathetic activity. However, the authors conclude that the awaking effect remained only for short time. Through a repeated application with varying temperatures, the effect could be extended, but this has to be further investigated in the future. Similar results through thermal stimuli were found in E. Schmidt et al. (2017).

2.5.2.2 Additional task-dependent stimuli

The first method of adding task-dependent stimuli can be realized through a variation of the environment, which is relevant for the driving task. Merat & Jamson (2013) investigated in a simulator study, if variable message signs, chevrons or rumble strips show a positive effect on attention. The results were mediocre; partially the measures were able to improve fatigue; however, the effects only had a short duration.

Another approach to add task-dependent stimuli is to gamify the driving task. For this purpose, different driving games were developed. Steinberger et al. (2017) investigated a gaming application that rewarded the maintenance and anticipation of speed limits. The application significantly improved speed behavior (e.g. driving speed, speeding intensity, amount of speeding). However, there was no effect on lateral control. Another gaming application was presented by Bier et al. (2019). The application included three games with the following instructions (p. 3): “maintain the lane as precisely as possible on straight stretches of the road; maintain the legal minimum distance to the vehicle in front as accurately as possible or maintain the current maximum speed as accurately as possible”. The gaming application led to less subjective fatigue, improved lane tracking, reduced speeding and a higher recognition of road signs.

Despite the promising results, games based on the driving task have one major drawback. The player’s driving behavior is used as the input for the games. As described in Chapter 2.2.4, especially partial-automation is a growing risk on passive driver fatigue. With increasing automation, more tasks are taken over by the vehicle. This reduces the number of available inputs for such games, which makes them presumably less attractive and effective.

2.5.2.3 Secondary tasks

Lastly, additional tasks while driving are performed to reduce passive driver fatigue. To the best of the author's knowledge, only cognitive secondary tasks were used. Neubauer et al. (2014) investigated the alerting effects of hands-free telephoning and a quiz game while driving. Both interventions elevated task engagement and improved lane tracking. However, both interventions showed no effect on reaction time to an emergency event. The impact of a phone call was also studied by Jellentrup et al. (2011) in a truck driving task with a mean speed of 40 kph. Drivers were more alert and awake during the telephone conversation. The alpha spindle rate diminished and the relative blink duration declined. However, both studies used telephone protocols with scripted conversations. In reality, phone calls can have diverse effects on emotion and cognition. The majority of literature suggest that telephoning has a negative effect on driving performance (Horrey & Wickens, 2004; Lipovac et al., 2017).

Another form of additional cognitive tasks while driving are quiz games. Verwey & Zaidel (1999) investigated a gamebox that included twelve games, e.g. quiz games and Tetris. The participants could choose the games as they wished without any restrictions. Using the gamebox led to a reduction of subjective weariness, frequency of line-crossing events, rapid steering movements and eyelid closures. Positive effects of quiz games were also found in the study by Gershon et al. (2009), leading to a reduced standard deviation of lane position, standard deviation of speed and standard deviation of steering angle. In addition, subjects felt significantly more motivated and less sleepy. The previous findings are supported by a study of Oron-Gilad et al. (2008). The authors observed alerting effects and mitigated performance deterioration through long-term memory quiz questions while driving.

3. Physical effects of static sitting

Chapter 3, 3.1, 3.2 and 3.4.2 were published in a largely similar form in Lampe & Deml (2022a).

The phrase 'Sitting is the new smoking' is published more and more frequently (Chau et al., 2019). Although this comparison has been criticized in the literature (Vallance et al., 2018), it reflects society's increasing perception of the health risks associated with static sitting. According to Sedentary Behaviour Research Network (2012, p. 540) sedentary behavior is defined as "any waking behavior characterized by an energy expenditure ≤ 1.5 metabolic equivalents while in a sitting or reclined posture". This definition is largely adopted in the literature by now (Tremblay et al., 2017).

C. E. Matthews et al. (2008) found that children and adults in the United States sit for 54.9 percent of their waking time, or 7.7 hours/day. Colley et al. (2011) estimated the amount of sitting in Canadian adults based on accelerometer data to be 69 % of their waking time, or 9.5 hours/day. Bauman et al. (2011) reported large differences in sitting time between different countries. They found the highest sitting rates for adults in Taiwan, Norway, Hong Kong, Saudi Arabia, and Japan (medians ≥ 360 min/day). In these countries, 18.6 - 22.2 % of adults sit between 361 – 539 min/day, and 27.2 - 34.9 % sit between 540 – 1020 min/day.

At least in Western countries the workplace can be seen as one major contributor to high rates of prolonged sitting time (McCrady & Levine, 2009). Certain professions are particularly exposed to long periods of sitting, including professional drivers (Thorp et al., 2012). Varela-Mato et al. (2016) for example found that bus drivers (in East Midlands, United Kingdom) sat more than 12 hours on working days and 9 hours on days off. For lorry drivers, 13 sitting hours were measured on work days and 8 hours on non-workdays (Varela-Mato et al., 2017). Gilson et al. (2016) found an average sitting time of 9.1 hours/day for Australian truck drivers. The health risks of sedentary time among truck drivers might be further aggravated by risk factors such as unhealthy foods at truck stops (Guest et al., 2020).

3.1 Causes and countermeasures of sitting-related metabolic and cardiovascular diseases

In general, higher amounts of sitting time are associated with all-cause mortality, cardiovascular diseases, cancer and type-2 diabetes (Diaz et al., 2017; Proper et al., 2011; World Health Organization, 2020). Warren et al. (2010) specifically examined the risk factors of sitting with relation to car usage. Subjects reporting to ride a car more than 10 hours/week had a 50 % greater risk of dying from cardiovascular disease than those reporting less than 4 hours/week of driving.

The magnitude of the listed negative health effects can be reduced and even compensated through physical activity (Biswas et al., 2015; Chau et al., 2013; Chomistek et al., 2013; Ekelund et al., 2016; Petersen et al., 2014; Warren et al., 2010). However, based on a systematic review by Ekelund et al. (2016), about 60 - 75 minutes of moderate physical activity[4] per day is necessary to achieve compensatory effects.

This exceeds common guidelines for physical activity, which are already rarely followed. The national guidelines of the American College of Sports Medicine and the Centers for Disease Control and Prevention recommend moderate-intensity aerobic physical activity for at least 30 min on five days per week or vigorous-intensity aerobic physical activity for at least 20 min on three days each week for healthy adults (Haskell et al., 2007). The World Health Organization (2020) recommends a weekly dose of at least 150 - 300 minutes of moderate-intensity aerobic physical activity or 75 - 150 minutes of vigorous-intensity aerobic physical activity.

In reality, Canadian adults on average execute 23 min/day of moderate to vigorous physical activity (Colley, 2018) and only 15 % accumulate 150 min/week (Colley et al., 2011). Miles (2007) found that only 35 % of men and 24 % of women in the UK achieved 30 minutes of at least moderate-intensity

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[4] According to Ainsworth et al. (2000), the intensity of an activity can be expressed in metabolic equivalents (METs). The metabolic rate of the activity under consideration is related to quiet sitting, which has a MET of 1 ($4184\ kJ * kg^{-1} * h^{-1}$). Moderate activity is defined in a range of 3 - 6 METs, vigorous activity > 6 METs. An example of an activity with 6 METs is cycling at 10 - 11.9 mph. For a detailed table of activities, see Ainsworth et al. (2000).

activity on at least 5 days of the week, which matches the numbers for US adults quite closely (Kruger et al., 2007).

These low numbers might be one important factor, why everyday non-exercise activity is seen as an important contributor to reduce all-cause mortality (C. E. Matthews et al., 2007; Weller & Corey, 1998). Traditional exercise programs often suffer high dropout rates of 50 % or more during the first year (Franklin et al., 2010). However, even small movements can add up to an increased total energy expenditure per day (Levine et al., 2000). Therefore, it is beneficial to reduce sedentary time with activity of any intensity in daily life (World Health Organization, 2020).

3.2 Causes and countermeasures for musculoskeletal disorders associated with sitting in vehicles

According to Punnett & Wegman (2004, p. 13) musculoskeletal disorders describe "a wide range of inflammatory and degenerative conditions affecting the muscles, tendons, ligaments, joints, peripheral nerves, and supporting blood vessels". Besides diagnosable syndromes, this also includes pain especially in the lower back whose cause is unknown. The authors add that in many countries, musculoskeletal disorders represent a substantial amount of all registered and/or compensable work-related diseases.

Numerous studies exist, that investigated musculoskeletal pain (MSP) among professional drivers. These studies are nicely summarized in the review by Joseph et al. (2020) including 56 studies from 14 types of occupational transport. According to the review, the total prevalence rates of MSP among professional drivers ranges within 43.1 % and 93 %, with a mean of 73 %. The following order was reported for the frequency of pain in the different regions of the body:

1. *Lower back* (range from 17 to 82.9 %, meta-prevalence rate 53 %)
2. *Neck* (range from 7.1 to 78.8 %, meta-prevalence rate 39.2 %)
3. *Upper back* (range from 2.6 to 60.3 %, meta-prevalence rate 25.5 %)
4. *Knee* (range from 5.6 to 36 %, meta-prevalence rate 21.8 %)
5. *Hip/thigh* (range from 2.7 to 22.2 %, meta-prevalence rate 19.5 %)
6. *Wrist* (range from 1.3 to 31.0 %, meta-prevalence rate 11.5 %)

7. *Ankle and elbow* with prevalence rates of 15.1 and 7.9 %

The IASS, which will be developed as part of this work, focuses on reducing pain in the most affected areas, i.e., the lower back and neck. For this reason, the countermeasures presented in this chapter are equally limited to these two bodyareas.

Risk factors and contributors for musculoskeletal lower back and neck pain are multifaceted and complex (Bovenzi, 2015; Joseph et al., 2020; Lis et al., 2007; Okunribido et al., 2006, 2008; Walker-Bone & Cooper, 2005). For the development of musculoskeletal pain due to driving, ergonomic, psychosocial and individual factors are mentioned (Alperovitch-Najenson, Santo, et al., 2010). Ergonomic risk factors include static and poor sitting posture (Alperovitch-Najenson, Katz-Leurer, et al., 2010; Alperovitch-Najenson, Santo, et al., 2010; Harish et al., 2021; Porter, 2002; Putra et al., 2021). Driving a vehicle is often characterized by loss of lumbar lordosis (Porter, 2002; Selvam & Arun, 2016), increased or decreased neck flexion (Selvam & Arun, 2016), forward head posture (Harish et al., 2021; M. Y. Lee et al., 2020; Putra et al., 2021; Selvam & Arun, 2016) as well as shoulder protraction and thoracic kyphosis (Putra et al., 2021; Selvam & Arun, 2016).

One way to treat chronic low back pain (CLBP) is with core exercises (França et al., 2010; Liddle et al., 2004; Unsgaard-Tøndel et al., 2010). Adequate functioning of the hip muscles is crucial to ensure active stiffness of the lumbar spine in addition to passive stiffness by osseous and ligamentous structures (Akuthota & Nadler, 2004; Neumann, 2010). Especially abdominal muscles are important as they prevent the pelvis from undesired and excessive anterior tilting when flexing the hips (Neumann, 2010). Numerous studies have shown that not only individual but all trunk muscles are involved in the generation of active stiffness (Akuthota & Nadler, 2004; Cholewicki & VanVliet IV, 2002; Grenier & McGill, 2007; Kavcic et al., 2004; McGill et al., 2003). Therefore, to improve CLBP, the whole core musculature should be trained, and not just individual muscles. Besides trunk muscles, strengthening of the m. gluteus maximus is suggested, as endurance of this muscle is decreased in patients with CLBP (Kankaanpää et al., 1998) and strengthening of this muscle further increases the efficacy of core-exercises against CLBP (Jeong et al., 2015).

As listed in the beginning of this chapter, forward head posture is listed as a contributing factor for neck pain in driving, which is further aggravated by sitting with slumped posture. This phenomenon is also known from the office and is referred to as the upper crossed syndrome (Caneiro et al., 2010; Kang et al., 2012). According to Page (2011) the upper crossed syndrome is associated with an hyperactivity of the m. trapezius pars descendens, m. levator scapulae, and the pectoralis muscles as well as an underactivity of the deep cervical flexors, the m. trapezius pars transversa, m. trapezius pars ascendens, and m. serratus anterior. Besides stretching exercises for the rhomboid muscles and the m. trapezius pars descendens, strengthening of the m. trapezius pars transversa and m. trapezius pars ascendens is proposed as a countermeasure by Bae et al. (2016), which is achieved for example with scapular retraction exercises (Harman et al., 2005; Kirupa et al., 2020; M. Y. Lee et al., 2020).

Promoting dynamic muscle activity has an additional purpose. The reason for this is, that during isometric contractions, such as sitting, blood flow and thus oxygen supply to the muscle is reduced even at low loads (McGill et al., 2000). This can lead to muscle fatigue (Kahn & Monod, 1989). During dynamic exercise, however, blood flow is increased during the relaxation phase (Saltin et al., 1998; Walløe & Wesche, 1988). In this way, oxygen supply to the muscle is ensured during dynamic exercise, at least up to moderate levels of exertion (Van Beekvelt et al., 2001).

3.3 Sitting comfort and discomfort

Various factors influence overall sitting comfort and discomfort. Besides characteristics such as the contour or material, these also include breathability and climate of the seat (Cengiz & Babalık, 2007; Kolich, 2008; Vlaović et al., 2016). Since the IASS does not aim to improve the seating climate and breathability, these factors will not be discussed in this thesis. According to De Looze et al. (2003) and Kolich (2008) two main reasons motivate the research in the area of comfort and discomfort. Firstly, both are decisive product differentiator for the consumer, but they also improve well-being and health. Such a relationship was for example found by Hamberg-van Reenen et al. (2008). The authors measured the participants' local discomfort in different body parts six times during the workday. Increased discomfort predicted an increases risk of back, neck and shoulder pain after three years (relative risk varied from 1.8 to 2.6). Therefore, discomfort and comfort might not directly affect sitting health, but they are important risk indicators. For simplicity, the terms seating comfort and seating discomfort are sometimes abbreviated to comfort and discomfort in the following chapters of this thesis.

3.3.1 Definition of sitting comfort and discomfort

There is general agreement that comfort and discomfort are feelings or emotions and therefore of subjective nature (De Looze et al., 2003). Both feelings are influenced by various environmental factors (physical, physiological, psychological) which are for example described in the comfort model of Vink & Hallbeck (2012). There is also a largely agreement that discomfort increases with time (e.g. Falou et al., 2003; Mansfield et al., 2015; Smith et al., 2015).

A large point of discussion is, however, whether sitting comfort and discomfort are the same concept or if they should be treated as related but distinct phenomena (De Looze et al., 2003; Kolich, 2008; Ulherr et al., 2018).

There are comfort models that make no differentiation between comfort and discomfort (e.g. Kolich, 2008). Some authors also use comfort and discomfort interchangeable in their publications (e.g. Ebe & Griffin, 2000). This also includes authors that state to measure discomfort, but use scales that range from 'extremely comfortable' to 'extremely uncomfortable' (Corlett & Bishop, 1976).

Other authors, in contrast, differentiate between comfort and discomfort and treat them as complementary entities. This view is strongly supported or even based on the work of L. Zhang et al. (1996). In the study the authors queried participants about their associations with comfort and discomfort. The answers were clustered with the help of multidimensional scaling as well as a cluster- and factor analysis. Discomfort was associated with biomechanical and physical characteristics (e.g. joint angles, muscle contractions, pressure distribution) which lead for example to pain, soreness, numbness and stiffness. In order to perceive comfort on the other, the subjects mentioned aspects that exceed neutral sensations. Comfort is associated with luxury, relaxation and refreshment, but it is also influenced by aesthetical factors. These findings were later confirmed with a factor analysis in another study (Helander & Zhang, 1997). The second study additionally revealed that comfort becomes secondary in the presence of discomfort. In other words, in order to perceive comfort, discomfort has to be on a low level. The differentiation between comfort and discomfort is for example supported by De Looze et al. (2003) and Kyung et al. (2008). Kyung et al. (2008) propose discomfort ratings to ensure basic seat requirements that mainly have the goal to prevent pain, and comfort ratings for advanced seat properties that aim at increasing the pleasure of the occupant.

3.3.2 Measurement methods of comfort and discomfort

More than 50 years ago, Shackel et al. (1969) already described the lack of consensus on how to best measure comfort, and until today no common or standardized method exists (Ulherr et al., 2018). In general, objective and subjective techniques are used to measure comfort and discomfort (De Looze et al., 2003; Ulherr et al., 2018). Subjective assessment can be regarded as a the more concrete measure as the seater is directly asked about his or her feelings (De Looze et al., 2003). For this reason, some authors state, that subjective methods are best to understand (dis-)comfort (Kolich, 1999). Objective measures in contrast are indirect measurement methods (De Looze et al., 2003; Ulherr et al., 2018). On closer inspection, these methods do not measure sitting (dis-)comfort itself, but causes or a correlates of it. De Looze et al. (2003) state that indirect measures can at best give an indication of an individual’s sitting comfort. However, according to J. Lee & Ferraiuolo (1993) objective methods have the advantage to be less expensive, time consuming and prone to measurement error and are thus expected to be more efficient (Kolich, 2003). A review of objective methods for the assessment of comfort and discomfort is provided by De Looze et al. (2003). These methods include for example pressure distribution, anthropometry, posture, number of body movements, muscle fatigue, spinal loading forces and foot volume change (De Looze et al., 2003; Kolich, 2003; Mehta & Tewari, 2000; Varela et al., 2019).

The cost-saving argument is likely to be particularly relevant in scenarios where many seats are tested in succession. When evaluating studies such as those in this thesis, the increase in efficiency might be rather small. Therefore, a direct measurement with subjective methods was preferred in this thesis. Another argument for the use of subjective methods is the fact that for none of the objective methods a clear and consistent relation with subjective experiences can be found in the literature.

For these reasons, the following chapters that list evaluation methods for (dis-)comfort are limited to questionnaires. The questionnaires can be clustered into (1) questionnaires about the seating, (2) questionnaires regarding the seater's perception and (3) questionnaires that directly query (dis-)comfort.

3.3.2.1 Questionnaires on the seating

The questionnaires in this cluster evaluate characteristics of the seat that are expected to have an influence on the perception of sitting. They do not query the feelings themselves. One example is the 'seat comfort survey' by Kolich (1999) in which the amount of lumbar support has to be rated from 'uncomfortable' to 'just right'. Similar questions can be found for a chair assessment in the publication of Shackel et al. (1969).

3.3.2.2 Questionnaires on the seater's perception

This group of questionnaires asks about conditions or feelings that are associated with (dis-)comfort. As an example the statement 'I feel stiff' in Shackel et al. (1969) aims at drawing conclusions about discomfort. Other questionnaires of this type were used, for example, by Porter et al. (2003) and Vlaović et al. (2016). An important questionnaire of this type is provided by Helander & Zhang (1997). In accordance with their assumption that comfort and discomfort are distinct feelings (see Chapter 3.3.1), the 'Chair evaluation checklist' explicitly queries both constructs separately. A shortened version of this questionnaire, titled as 'wellbeing questionnaire' can be found in Varela et al. (2019).

3.3.2.3 Questionnaires that directly query (dis-)comfort

The third group comprises questionnaires that directly ask for the sensation of (dis-)comfort. This includes scales for overall (dis-)comfort (Corlett & Bishop, 1976), but also the use of body maps for more detailed information (e.g. Hamberg-van Reenen et al., 2008; Mansfield et al., 2015; Varela et al., 2019). A body map is an illustration of a human body that is divided into different anatomical zones. Each zone of the map is now rated separately. The number of zones included in the body map varies greatly. Within the literature available to the author, the number ranges from 6 to 36 (Corlett & Bishop, 1976; Falou et al., 2003; Hamberg-van Reenen et al., 2008; Mansfield et al., 2015; Smith et al., 2015; Varela et al., 2019).

However, regardless of whether overall discomfort is evaluated or body maps are used, there is no general standardization regarding the scale endpoints used. These include for example ‘very comfortable’ to ‘very uncomfortable’ (Smith et al., 2015), ‘no discomfort’ to ‘unbearable discomfort’ (Falou et al., 2003), ‘not uncomfortable’ to ‘extremely uncomfortable’ (Mansfield et al., 2015). This diversity of endpoints describes a major problem with directly asking respondents about comfort and discomfort. In order to evaluate (dis-)comfort validly, one must first know what exactly the two constructs describe. This problem is also recognized by Ulherr et al. (2018) who add, that the term discomfort does not exist in many languages, with German as one example. However, even if the word discomfort exists in the language of the respondents, the issue remains that there is no consensus in the scientific literature about what describes (dis-)comfort. This missing consensus is also reflected in the questionnaires. For example Mansfield et al. (2015) state to measure discomfort but use the term ‘uncomfortable’ as endpoints.

Considering the fact that not even research has the same definition of (dis-)comfort, it is difficult to assume that an average person knows the meaning of (dis-)comfort. Therefore, if (dis-)comfort is directly measured, the questionnaire should at least provide information about the meaning of both feelings for the respondents.

There are also findings in the literature that should be considered when using body maps for the purpose of more accurately determining the anatomical location of the perceptions of (dis-)comfort. Whether the additional time required for the use of body maps is justified depends on the research question. Kyung et al. (2008) queried comfort and discomfort with overall rating scales and body part questionnaires. They observed that the subjects used averaging processes. That means subjects averaged the comfort ratings of the individual regions for the overall comfort rating. The overall discomfort was predominantly determined by the highest rating on the body map. The observations regarding discomfort were also found by Falou et al. (2003) and Mansfield et al. (2015). Consequently, the overall evaluation could often be sufficient to gain first insights in early evaluation stages.

Finally, for completeness, it should be mentioned that there are other ways to obtain more detailed information about sensations apart from their location. One example is asking about the type of discomfort experienced (vibration, local pressure, heat, cramps or tingling), as is done in Falou et al. (2003).

3.4 Technical approaches to reduce negative physical effects of static sitting in vehicles

Different countermeasures against negative physical effects of static sitting in vehicles already exist today. Among these, measures that can be used while traveling are advantageous from the author’s point of view. As described in Chapter 2.5.1, studies that investigated fatigue and sleepiness behind the wheel, found that taking a break is considered useful but hardly taken. This means drivers do not take breaks when being in a poor condition and thus in acutely dangerous situations. Therefore it seems unlikely drivers would take a rest for preventive measures against negative physical effects which are often accompanied by longterm health problems such as metabolic and cardiovascular disease.

To the best of the author’s knowledge, countermeasures during travel are limited to seating systems, with exception of one publication. As there is not yet a consensus on the classification of the seating systems, these are categorized into passive dynamic seating systems (PDSSs) and active dynamic seating systems (ADSSs) in this thesis. In PDSSs, moving elements in the seat passively mobilize the passenger. ADSSs on the other hand encourage the user to perform active movements himself. The majority of the countermeasures were evaluated with electromyography (EMG), which provides information about muscle activity. As described in Chapter 3.2 dynamic muscle activity shows the potential to reduce musle fatigue that is caused by static muscle activity. Therefore, the countermeasures are intended to reduce the static sustained activity of the muscles, while promoting dynamic muscle activity.

The only non-seating countermeasure is described by Menotti et al. (2015). The authors investigated a neck balance system in combination with a lumbar support, with the aim of reducing muscle fatigue in the automobile. The neck balance system consisted of a baseball type cap that included two weights of 200 gram attached to the occipital area. Muscle activity in the lower back was lowered through the devices during accelerations and decelerations of the vehicle. Activity of the neck extensors muscles was lowered only during acceleration. No effect was found on neck flexors muscles, pitch of the head and comfort. Unfortunately, the devices were not evaluated during a constant ride without substantial acceleration. In addition, the measures were investigated in combination only. Therefore, it is difficult to differentiate between the effects of the lumbar support and the neck balance system.

3.4.1 Passive dynamic seating systems

Durkin et al. (2006) compared three seats with different lumbar massage systems with a control seat in a 1 h simulated driving task. They found no effects on muscle activity from the right and left thoracic and lumbar erector spinae. They also found no effects on discomfort between seats. However, the authors found a significantly increased skin temperature in the right thoracic and lumbar erector spinae for all three massage seats, which is associated with improved muscle blood flow and oxygenation.

Franz et al. (2008) investigated a car massage seating system that rotated the vertebrae alternately in a 2 h driving task. The authors found a significantly decreased EMG activity for the musculus (m.) trapezius pars descendens. Activity in the m. rhomboideus was lowered as well; however, the comparison just missed significance. The m. longissimus thoracis was also captured, but as results are not reported, it can be assumed that no significant differences were found. The lowered muscle activity in the shoulder area is associated with increased relaxation. Similar results were found in a follow-up study with a more or less identical study design (Franz, Zenk, et al., 2011).

Two studies by Kolich and colleagues investigated different forms of lumbar massages through micro-adjustments of the lumbar support. The aim of the concept is to continuously vary the muscle activity to reduce static activity (Kolich & Taboun, 2002). In the first study, Kolich et al. (2000) examined the effects of the system on lower back muscle activity (sacrospinalis muscle). They compared five massage conditions that included different massage intervals with a control condition. The sitting time in the study was one hour. Lowered muscle activity was only found for one-minute lumbar massage every 5 minutes. In the second study, Kolich & Taboun (2002) investigated the activity of the m. erector spinae together with discomfort ratings. They compared eight different massage conditions, again with varying massage intervals, over two hours. They found a significant correlation between both measures (r = -.79, p = .02). That said, the lower the discomfort rating, the larger the decrease of muscle activity over time.

Varela et al. (2019) evaluated a motion seating system. Two different movements, fore-aft and cushion-backrest, were compared to a control condition. Both movement conditions showed a tendency for lower overall discomfort as well as local discomfort in the neck, shoulders, lower back and ankles. However, significant discomfort improvements through the seat movements occurred only after 60 minutes in the buttock region. Another study that tested the effects of cushion-backrest movements was conducted by van Veen et al. (2015). The authors captured significantly less movements in the seat, which is associated with lower discomfort. This assumption was supported by improved subjective comfort and discomfort.

3.4.2 Active dynamic seating systems

To the best of the author’s knowledge, only three publications exist that describe active dynamic seating systems in vehicles. Among those, the publication by Hiemstra-van Mastrigt et al. (2015) is the only one, that investigated an ADSS in a car. The seating system comprised a ball balance game that was controlled by pressing the upper body left- or rightwards into the seat back. The system led to a significantly higher heart rate, and variability of muscle activity in six postural muscles. Additionally, the user experience was rated on a questionnaire adopted from the ‘Chair Evaluation Checklist’(Helander & Zhang, 1997). The participants felt significantly more challenged, fit and refreshed. Bouwens et al. (2018) investigated an ADSS in an airplane quite similar to that in Hiemstra-van Mastrigt et al. (2015). However, the users controlled the ball balance game by lifting or extending the legs forward. The authors found a significant improvement of overall comfort and discomfort even though no benefit on localized musculoskeletal discomfort was found. Westelaken et al. (2008) provide another technical solution to play games with body movements in an aircraft seat. The system used a grid of Force Sensing Resistors, whose data was processed with a neural network. The neural network was trained to classify nine different gestures, three of which can be used to control a game. However, the authors did not test the system for efficacy.

4. Concept of the interactive seating system

Chapter 4.2.2.1 and 4.2.2.2 were published in a largely similar form in Lampe & Deml (2022a).

The aim of this thesis is to provide an interactive seating system that addresses both passive driver fatigue and negative physical effects of static sitting in the vehicle. Chapter 4.1 describes the concept of the IASS. Chapter 4.2 explains, why conceptualizing the IASS in this manner is advantageous to meet both before mentioned goals at the same time.

4.1 Description

Figure 5 illustrates the IASS. The basis is a series production seat (Mercedes-Benz GLE V167) that comprises a massage seating system (MS) with nine air bladders (ABs) mounted in the seat back. The positions of the ABs in the backrest are highlighted with color in Figure 5. The program of the MS includes a shoulder and a lumbar sequence. The five ABs marked in red in Figure 5 are used for the lumbar sequence, the blue and green ABs inflate alternatingly during the shoulder sequence. When the air bladders inflate, they are felt as pressure points at specific locations on the passenger's back. The user is now encouraged by an audio track to press against these pressure points with specific movements. Each sequence aims at initiating different movements, which are described in detail in Chapter 4.2.2. If the user follows the movement instruction, a positive feedback is provided by switching on the ambient lighting and vibrating elements in the seat cushion.

Before the actual program starts, an introduction describes the basic movement task and gives instructions regarding the sitting posture: a) Slide your buttocks as close to the seat back as possible; b) Assume an upright position; c) The back must maintain contact with the seat back, so avoid hollowing the back.

Prior to the first use or during appropriate situations (e.g. for passengers only, during autonomous driving …) a user interface is displayed to assist in learning the movement task. As different user interfaces were used in the three studies of this thesis, these are described in the method sections in Chapter 5.3.2, 7.2.1 and 8.2.1.

Figure 5: *Schematic representation of the interactive seating system. Air bladders used for the right shoulder sequences are marked in green, for the left shoulder sequences in blue and for the lumbar sequences in red.*

4.2 Theoretical background

A lack of physical activity is the primary cause of sitting related metabolic and cardiovascular diseases (see Chapter 3.1). In addition, dynamic muscle contractions show the potential to reduce musculoskeletal disorders caused by static sitting (see Chapter 3.2). Therefore, ADSSs are supposedly more suitable than PDSSs to counteract these problems because they initiate active movements from the passenger. This assumption is also shared by Varela et al. (2019), however, the authors state that active movements of the driver are not compatible with driving. In order to guarantee a good driving performance, the driver’s hands should be kept on the steering wheel, the eyes on the road and both feet near or on the pedals (Graham & Carter, 2000; Van Erp & Van Veen, 2004). With current ADSSs, this is not possible.

The only ADSS in the vehicle that was found in the literature (Hiemstra-van Mastrigt et al., 2015) uses a display for interaction. Therefore, the systems is only suitable for passengers and not for drivers. The interaction would interfere with driving because it requires taking visual focus off the road. However, in many countries, drivers sit mostly alone in the vehicle. In Germany, for example, the average occupancy rate was around 1.5 persons in 2002, 2008 and 2017 (Follmer & Gruschwitz, 2019). Consequently, only few people would benefit from an ADSS for passenger seats.

Therefore, this thesis investigated whether it is possible to design an ADSS that represents a suitable additional task and may even counteract passive driver fatigue and thus improve driving performance in monotonous situations (see Chapter 2.5.2). In order to achieve this, two main aspects are different to current ADSSs. The IASS aims to provoke more targeted and slower body movements compared to gaming applications and no display is necessary for interaction.

4.2.1 Interaction

The decision for the interaction design was made under consideration of the *Multiple resource theory* (Wickens, 2002, 2008). The central aspect of the theory postulates, that greater interference between two tasks occurs if they share the same stages, sensory modalities, codes and channels of visual information.

As driving mainly demands visual perception, the system uses tactile (air bladders) and auditory (audio track) modalities to initiate the movement task. Feedback is provided via tactile (vibrating elements in cushion) and peripheral visual modalities (ambient lighting). Here, it is important to note, that the Multiple resource theory distinguishes between *focal* and *ambient* vision. Focal vision is almost always foveal and is required for fine detail and pattern recognition (e.g. reading text). Ambient vision involves mainly peripheral vision used for sensing orientation and ego motion (e.g. walking through environment). As the ambient lighting illuminates a large part of the interior, it is recognizable with ambient vision while the gaze remains on the road. Especially at night, when a particularly many weariness-related accidents occur, the illumination creates a great contrast to the dark interior. Blue color was chosen, as shortwave light is associated with an awakening effect (see Chapter 2.5.1). During the day, the contrast might be less present, which is why vibrating elements in the seat cushion are additionally used for feedback. The advantage of such a multimodal feedback is, that the user can switch between modalities and use the one that is better suited to the current situation (Vilimek et al., 2007). The benefit of combined visual and tactile feedback was for example shown by Van Erp & Van Veen (2004). The authors developed a tactile navigation system with vibrators mounted in the cushion. The vibrators were used as tactile modality only and as multimodal modality in combination with visual symbols. Both modalities received lower ratings of mental effort in comparison to an exclusive presentation of the visual symbols. In addition, significantly faster reaction times were measured for the multimodal modality.

According to the Multiple resource theory, it would also be possible to provide the feedback in auditory form. However, the author made the decision not to use this modality. On the one hand because the repetitive audio signals might disturb the user in the long-term (Pielot et al., 2008) but also because listening to music or receiving navigation messages would be impossible while using the IASS with audio feedback. Once the user understands the movement task of the IASS, the auditory instruction can be muted, but initiation and feedback signals have to be permanently present.

4.2.2 Sequences and exercise selection

The IASS consists of two main sequences. As described in Chapter 4.1 these include the inflation of different air bladders. A single program run lasts for 6:08 minutes and each sequence is included twice. The length of each sequence is given in Table 2. Within one sequence, the corresponding air bladders are inflated and deflated successively with varying intervals. In this way, the program is expected to be more diverse and thus more exciting for the user. The exact inflation of the air bladders also depends on factors such as the speed of inflation. However, such a detailed specification is not necessary for this work. Therefore, approximated times to a tenth of a second are given in Table 2. During the shoulder sequence, the air bladders in the left and right shoulder region inflate alternately. For the shoulder sequences, the listed inflation and deflation times refer to one air bladder.

Table 2: *Sequence lengths and corresponding inflation and deflation times of the air bladders.*

Sequence	Sequence duration	Inflation time (approx.)	Deflation time(approx.)
Lumbar 1	0:00 - 1:32 min	9.8 sec	5.5 sec
Shoulder 1	1:33 - 2:47 min	6.9 sec	0.5 sec
Lumbar 2	2:48 - 5:01 min	9.0 sec	4.5 sec
Shoulder 2	5:02 - 6:08 min	2.9 sec	0.5 sec

4.2.2.1 Movement of shoulder sequences

The user is asked to apply pressure against the shoulder air bladders by rotating the upper body on the longitudinal axis while pushing the scapula towards the seat back. During the execution, the torso should be braced by contracting all core muscles while the sitting position should remain upright. The sequence aims at initiating scapular retraction to improve musculoskeletal pain in the neck and upper back region. Besides activating the core muscles, this exercise is expected to activate the m. trapezius pars transversa and m. trapezius pars ascendens as recommended by the literature to reduce the upper-crossed-syndrome (see Chapter 3.2).

4.2.2.2 Movement of lumbar sequence

During the lumbar sequence, the instruction is to retract the belly button and then tilt the hip backwards. Throughout the exercise, the sitting position should remain upright. The movement is based on the draw-in maneuver, which is a common exercise to reduce low back pain by improving lumbar stabilization (Jeong et al., 2015; Jung et al., 2014; Richardson & Jull, 1995).

5. Study I – Definition of sensor locations

5.1 Abstract

For detecting the user's interaction with the IASS, pressure sensors had to be integrated into the seat back. For this purpose, this chapter reports a study that was conducted to specify optimal pressure sensor locations. In this context, a new approach for the analysis of seat pressure distribution images (SPDI) is proposed. The data was analyzed with *Statistical Parametric Mapping* (SPM), a statistical method that is commonly used to analyze data from Functional Magnetic Resonance Imaging studies. By converting the 527.250 SPDI that were captured in the study into 12 maps that include least-square estimates- as well as statistical values, SPM allowed making inferences about regional specific effects. In this way, the study revealed areas in the seat back that differed significantly between (1) interaction and (2) no interaction with the system, representing the optimal locations of the pressure sensors.

5.2 Introduction

As described in Chapter 4 the IASS is intended to detect the user's movements in the seat and provide feedback. A logical precondition for this is that the system can detect the user's interaction. Comparable to Hiemstra-van Mastrigt et al. (2015), it was decided that the detection of the movements should be carried out via pressure sensors in the seat back. However, in contrast to the system described by Hiemstra-van Mastrigt et al. (2015), the new IASS will use air bladders as task mediators. This creates a particular challenge for the integration of the pressure sensors in the seat back.

5.2.1 Challenges in the integration of pressure sensors for the IASS

Based on the data from the pressure sensors, an algorithm shall later detect whether or not the user is pressing against the air bladders in the seat when these are inflated. While it seems obvious to place the sensors directly on the air bladders, since the user applies pressure against these points in the seat back, it must be considered that the air bladders' main function is to exert pressure against the body. Therefore, a strong increase in pressure also occurs in these areas even when the passenger is not interacting with the system. Accordingly, the key challenge is to find locations in the seat back that provide pressure data that can detect an interaction, despite the pressure increase of the air bladders themselves.

A solution to improve classification of pressure changes due to actual interaction could be to use extensive data. The whole seat could be sensed and evaluated with advanced evaluation methods such as neural networks as described in Mitsuya et al. (2019). Current research has developed seats with smart textiles that can sense the entire seat surface. However, up to date, smart textiles in seats are still in the development stage and serial integrations are rare in the automotive industry (Van Langenhove, 2015).

Therefore, this is not a viable solution at the moment, so the IASS had to be equipped with single sensors with limited size. In order to increase the detection reliability of the algorithm, it is crucial to place the individual sensors at locations in the seat that provide the best possible data in order to distinguish between (1) interaction and (2) no interaction. Therefore, one crucial part in the development of the system was to identify these optimal sensor locations in the back rest. One sensor had to be installed for each group of ABs of the massage system (lumbar, left shoulder, right shoulder as described in Chapter 4), which corresponds to three sensors in total. The decision for three sensors was made because it was expected to be the best trade-off between the number of sensors and the quality of detection rate. The sensor locations should be valid (1) for different persons within the relevant anthropometric percentile limits and (2) for different seat adjustments. Following the standard, the relevant percentile limits were defined as the sitting height between the 5th percentile for women and the 95th percentile for men (Kolich, 2003). In conclusion, the key challenge was to find locations in the seat back that provide pressure data that can detect an interaction, regardless of the pressure increases from the air bladders themselves.

5.2.2 The approach to define pressure sensor locations with SPM

For the investigation of the best sensor locations, a subject study was conducted. The aim of the study was to compare pressure distributions with and without interaction. To consider the entire seat, pressure distribution mats were used for data acquisition. The goal of the analysis was to identify areas in the seat where the pressure data most likely allowed for a possible detection of both states: (1) interaction and (2) no interaction. The general approach was to determine areas in which the most statistically significant different pressure changes occur between the two states. The lower the p-value, the higher the probability, that the pressure values in both states come from different ‘populations’ (Field et al., 2012). The basic assumption is, that a later algorithm can better differentiate between both states, if it is fed with data, in which states (1) and (2) form different ‘populations’. Consequently, the study searched for the locations with the lowest p-values when comparing the two states.

Further improvement of the algorithm was expected if the pressure data between the two states differed not only in terms of amplitude increase, but also had inverse magnitudes. If areas exist that show increased pressure values during the inflation of the air bladders (whether due to the air bladders or an interaction), there could also be areas that show decreased pressures in return.

Since the sensor locations had to be defined accurately, the pressure data analysis had to be performed with high spatial resolution. Nowadays pressure distribution mats consist of fine sensing grids, which deliver accurate and extensive data. The limiting factor is the conventionally used methods for analyzing this data. Currently, three common ways of evaluating interface pressure are used. In the first approach, the pressure distribution images are subjectively evaluated by an examiner with regard to distinctive features, e. g., pressure peaks or topography (Oudenhuijzen et al., 2003; Stinson et al., 2003). In the second approach, single parameters are calculated from the pressure distribution images. The single parameters include, for example, contact area, average pressure, peak pressure, pressure gradient and pressure change (Gyi & Porter, 1999; Na et al., 2005; Paul et al., 2012; Porter et al., 2003; Romano et al., 2019). The third approach is to use body maps. A body map is a sort of template that subdivides the pressure distribution into different anatomical areas. Afterwards, the previously listed single parameters are calculated for each of the anatomical areas (Mergl et al., 2005; Park et al., 2013).

All three methods calculate single parameters for large areas in the seat. This processing step merges the extensive information of multiple sensor points into a single value. This helps to reduce the amount of data, but it comes with the cost of ignoring most of the data, too. This procedure is referred to as ‘subsampling’ and might lead to a conflation of pressure differences, obscuring or even reversing statistical trends (Pataky et al., 2008).

Although the use of body maps has a higher resolution compared to the other two procedures, this method poses an additional problem. The practical procedure is to orient and adjust the zones of the body map to the subjects’ width and size as well as to the distribution of pressure (Mergl et al., 2005; Porter et al., 2003). Consequently, the defined zones differ between subjects. Nonetheless, even if identical zones for all subjects were used, areas were still determined arbitrarily. Pataky et al. (2008) described this problem in their analysis of foot pressure distributions. Since the zones defined for seat pressure distributions usually cover larger areas and require even more sensors than foot pressure distributions, the above issues might be pronounced.

As a solution to the problem of subsampling, Statistical Parametric Mapping (SPM) was used for analyzing the seat pressure distributions. SPM was initially used to evaluate data from Functional Magnetic Resonance Imaging studies, which investigate where brain activity occurs under certain conditions (Friston et al., 1994). SPM uses a univariate mass approach, meaning that statistical tests are performed at the pixel level. In this way it is possible to identify locally-dependent effects. In the meantime, other authors applied SPM in biomechanical studies to analyze foot pressure data (Panagiotopoulou et al., 2012; Pataky et al., 2008), heal pad stress and femoral strain fields (Pataky, 2010) or quantitative computed tomography (W. Li et al., 2007).

5.2.3 Study objective

The goal of the study was to define where the pressure sensors for the IASS should best be located in the seat back. In particular, it was of interest whether the sensors should be placed directly on the air bladders or in other areas. Two conditions, one (1) with interaction and one (2) without interaction were compared. SPM was used to clarify with high spatial resolution: a) Where do the lowest p-values occur and b) do the pressure values in these areas only change with different amplitudes or also in opposite directions.

5.3 Setup

The measurement setup is shown in Figure 6. The investigation was carried out in the laboratory with a stationary vehicle. This means, that the participants sat in a real vehicle, but they did not drive during the study. The basis for the laboratory setup was a Mercedes-Benz GLE (V167 series) equipped with the MS that was described in Chapter 4. The MS was started by an external controller which was connected and synchronized to a pressure distribution mat (Interface Force XSensor LX100:48.48.02, 48 x 48 Sensors, 10 Hz sampling frequency, 0.07 – 2.7 N/cm^2 measuring range) and a microcontroller (Arduino Uno). The pressure distribution mat was affixed to the seat with adhesive tape to guarantee the same position over the whole study. In the active conditions, where the IASS was used (described in Chapter 5.4.1), various forms of instruction and feedback were used to ensure that the subjects' movements had the best possible execution. The microcontroller started an audio track that explained the desired movements in detail. In front of the car, a screen was positioned that showed a user interface. The user interface included a picture sequence to illustrate the currently inflated air bladders and another picture sequence, showing a mannequin that demonstrated the desired movement execution. In addition, the live image of the current pressure distribution was depicted.

5.4 Experimental Protocol

5.4.1 Conditions

The study included two types of conditions: active and passive. Within the study, the active condition occurred twice and the passive condition once. In the analysis, however, the two active conditions were treated as one active condition.In the active condition, subjects had to interact with the massage system as intended for the IASS, i. e., performing various movements against the alternating inflating air bladders (see Chapter 4). During the passive condition, subjects were instructed not to interact with the seat, meaning to sit in the seat and let themselves being mobilized while the massage system operated.

It is important that in this study, the left and right air shoulder bladders are categorized in two separate sequences. This means that the massage program is equivalent to the one described in Chapter 4, but contrarily to the other chapters, it is divided into three sequences in this study. These are (1) lumbar sequence, (2) right shoulder sequence and (3) left shoulder sequence. The reason for this is, that the movements in the shoulder sequence are similar for both directions, but it was defined, that each side receives an own sensor for detecting the interaction (see Chapter 5.2.1).

As described more detailed in Chapter 4.2.2, the instruction for the active condition was to apply pressure against the shoulder bladders by rotating the upper body on the longitudinal axis and pushing the scapula towards the seat back. To exert pressure against the air bladders in the lumbar region, the subjects were asked to retract the belly button and tilt the hip backwards.

5.4.2 Procedure

All subjects wore loose shorts and shirts without seams and pockets to avoid systematic effects on the seat pressure distribution. At the beginning of the study, the subjects were asked to adjust the seat

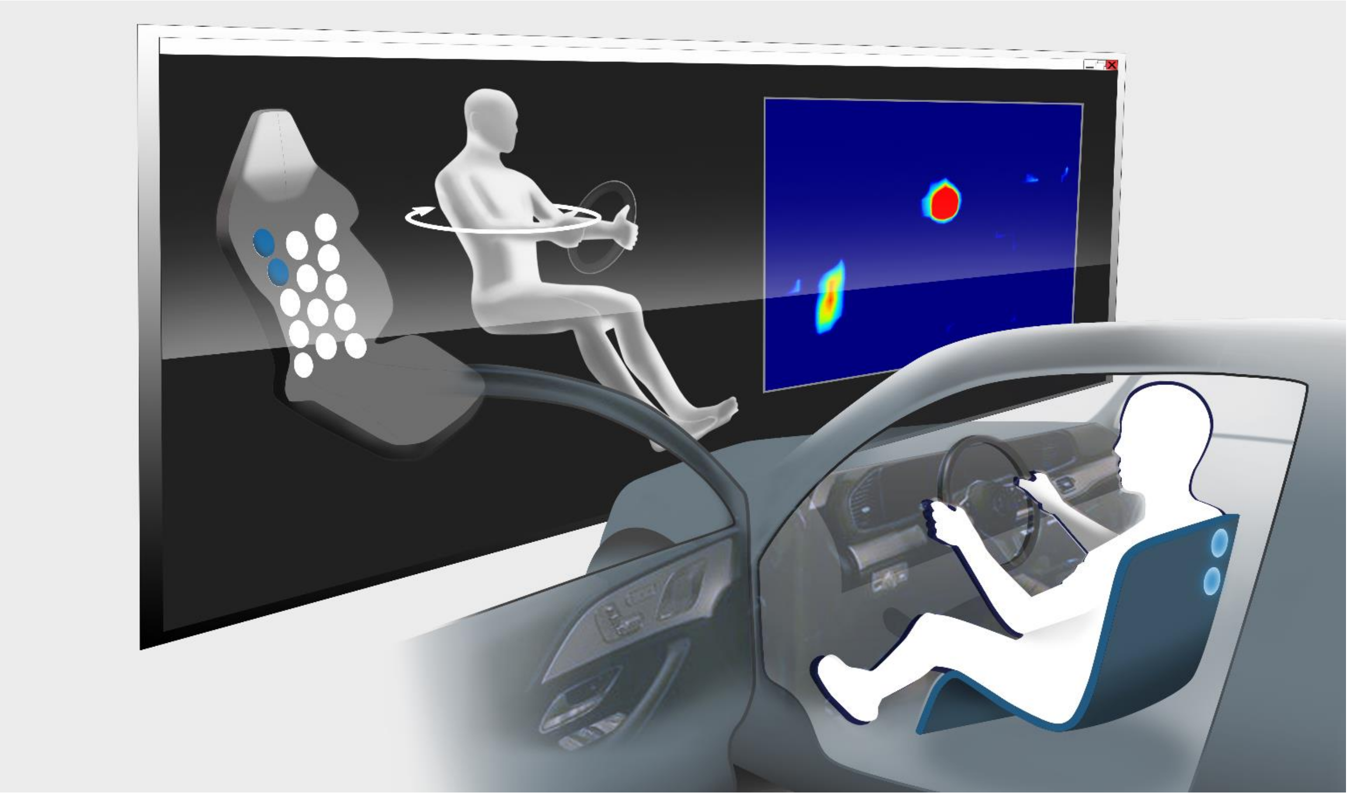

Figure 6: *Schematic illustration of the measurement setup.*

individually until they felt comfortable. The following adjustments could be made: Seat backrest inclination, seat height, seat cushion length, seat cushion inclination, seat fore-and-aft position. Each subject maintained the same seat adjustment during the whole study. Before each condition an introduction was played that gave instructions regarding the sitting posture: a) Slide your buttocks as close to the seat back as possible; b) Assume an upright position; c) The back must maintain contact with the seat back, so avoid hollowing the back; d) Keep both hands on the steering wheel, feet on the pedals, and gaze forward. The investigators controlled whether these positions were adopted, which was the case for all subjects. Each condition contained one program run of the MS, lasting for 6:08 minutes followed by a resting time interval (TI) for 1:47 minutes. During the resting TI, the air bladders were turned off and the subjects did not interact with the system. The experimental design followed a within-subjects design with repeated

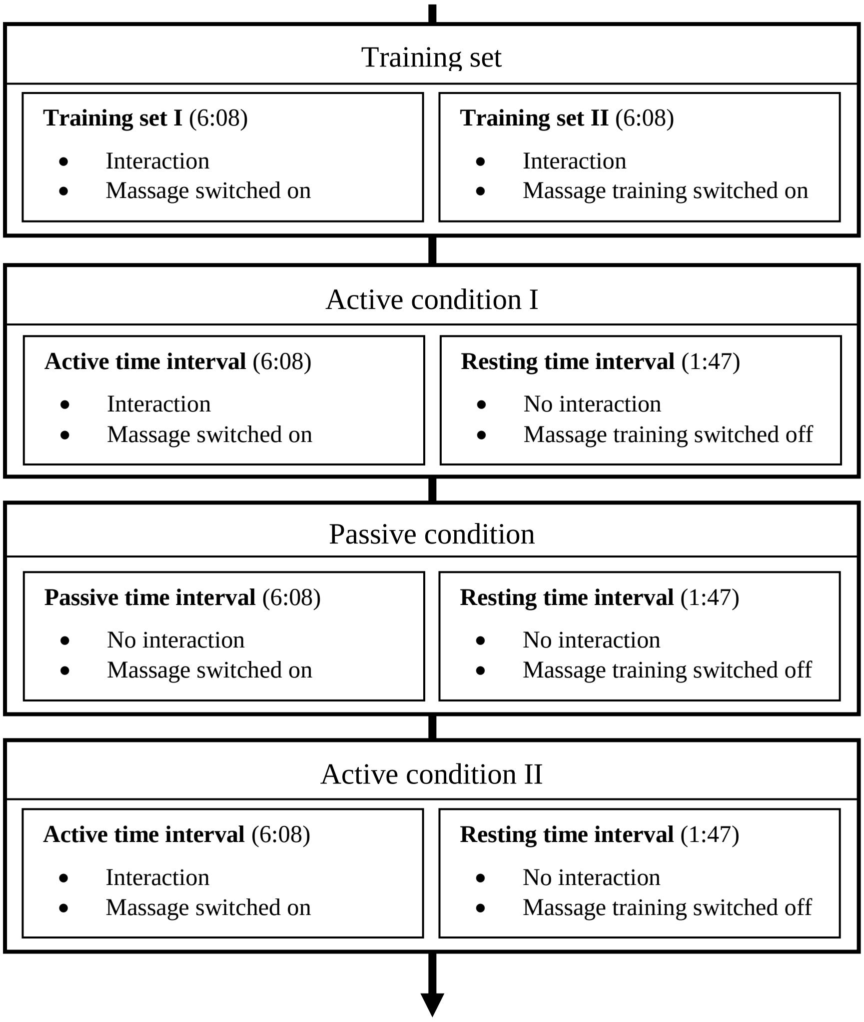

Figure 7: *Schematic representation of the experimental design.*

measures. The study consisted of two active conditions (ACs) and one passive condition (PC) as illustrated in Figure 7. The order of conditions was active condition – passive condition – active condition. Because the subject's movements served as a benchmark to classify the sensor locations, it was important to guarantee movements with a good execution. Therefore, subjects performed two training runs of the active time interval before the actual measurements. After each training run, subjects received movement corrections from the investigators if necessary. Because the subjects consequently sat for 15 minutes in the seat before the actual measurements started, the preceding training also had the side effect of stabilizing the temperature between the seat and subject to avoid systematic drifts of the data due to changes in interface temperature.

5.4.3 Subjects

Forty subjects participated in the study. Because the measurements of three subjects were incomplete due to technical problems, the study included 18 male and 19 female (N = 37) valid data sets. The mean age of the sample was 41.2 years (± 11.3 years, range from 21 to 58 years), mean body mass 77.9 kg (± 17.5 kg, range from 49.8 to 140.4 kg), mean sitting height 89.5 centimeters (± 4.4 centimeters,

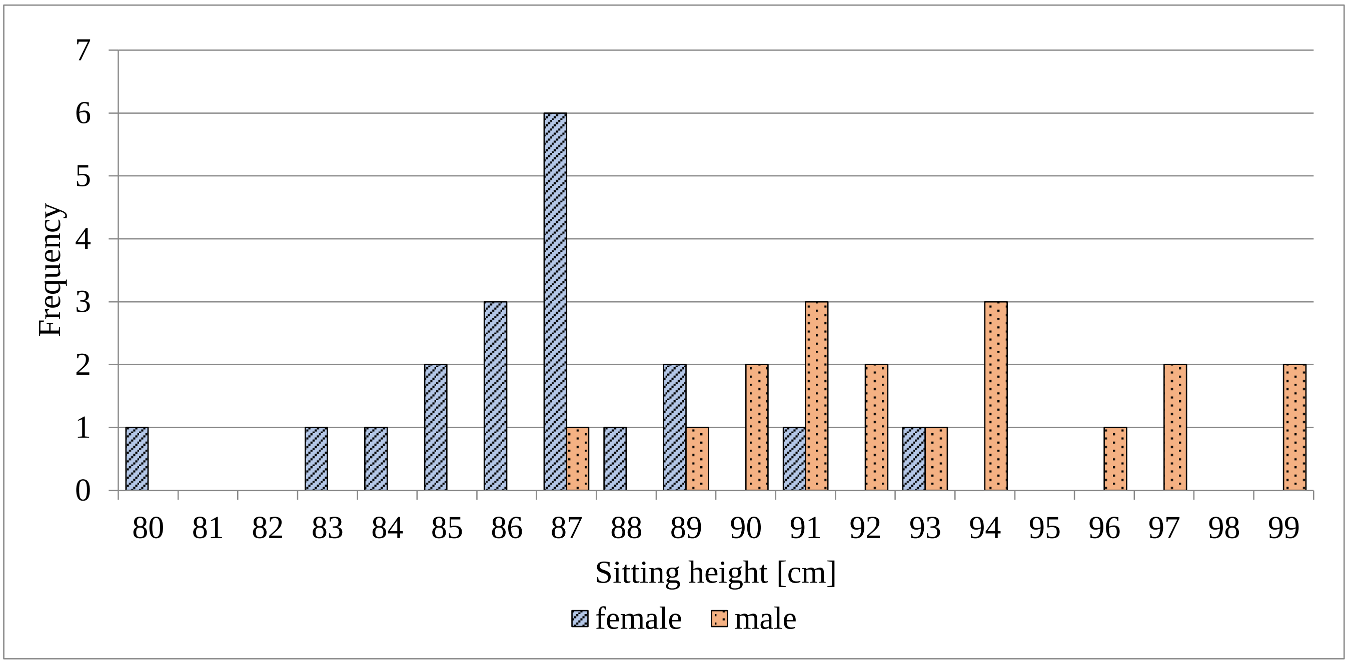

Figure 8: *Histogram representing the frequencies of sitting height among the subjects.*

range from 80.0 to 98.5 centimeters), and mean height 169.0 centimeters (± 9.0 centimeters, range from 153.5 centimeters to 189.5 centimeters). As it can be expected that the optimal sensor locations might depend on the users' anthropometry, subjects were selected with a sitting height preferably distributed between the 5th percentile for females and the 95th percentile for men. According to the German Institute of Standardization (Deutsches Institut für Normierung e.V., 2015) the sitting height should thus range between 81.0 to 96.5 centimeters, which was well covered by the sample. Figure 8 shows a histogram representing the frequencies of sitting height among the subjects. Before participating in the study, each subject gave written informed consent.

5.5 Statistical Parametric Mapping

In total 527.250 SPDI were captured (37 subjects $*$ 3 conditions/subject $*$ 475 seconds/condition $*$ 10 frames/second). The SPDI were analyzed with Statistical Parametric Mapping. The active conditions were merged together into one active condition and then compared to the passive condition using a t-test. The comparison was performed separately for each of the three sequences of the massage program (lumbar-, right shoulder-, left shoulder sequence).

Statistical Parametric Mapping (SPM) is a statistical method based on general linear models. More specifically, the model's least-square estimates are used to make comparisons between conditions. The procedure is applied to each data point, which allows testing hypotheses about regionally specific effects.

Following (Friston et al., 1994), the resulting residuals (e_{ij}) of each general linear model must be normally distributed, because this is in a conservative view, an assumption to use parametric tests in statistics. However, KS-tests revealed that the residuals were not normally distributed for any of the sensor points. As an example, the residuals of one of the seven most significant sensors of the lumbar sequence (see Subsection 5.5.1) are shown in Fig. 9. Because the distributions were still very symmetrical and the t-test is often described to be robust against a violation of a normal distribution (Lumley et al., 2002), SPM was still considered to be an appropriate statistical method for the dataset.

The following steps describe the application of SPM to seat pressure distribution images (SPDI). In step a) the need of image preparations is discussed. Step b) describes the application of a general linear model to each sensor point. In step c) the scaling parameters of the general linear model are calculated and visualized. Step d) shows an intermediating step to reduce irrelevant data points. Step e) explains the generation of contrast images to show the mean difference between conditions. The final steps f) and g) clarify the procedure to make statistical inferences between conditions with the help of t- and p-maps. Data processing was realized in Mathworks® Matlab® R2018b.

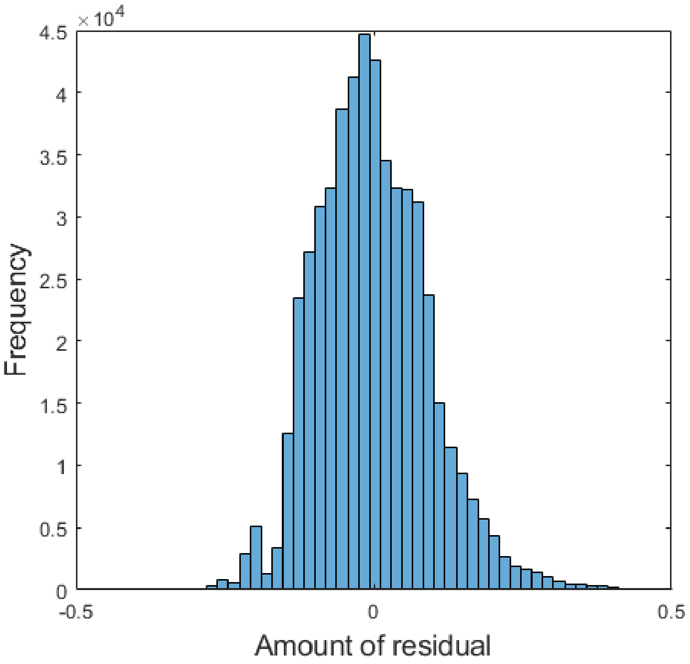

Figure 9: *The figure shows the distribution of one of the seven most significant sensors of the lumbar sequence. The distribution is non-normal but approximately symmetrical.*

a) *Image preparation*

Typically, SPM is used to make inferences about specific anatomical regions, such as brain areas in the case of fMRI studies. Because anatomical structures differ in size between subjects, it is usually necessary to transform pictures in size and orientation, aiming that anatomical regions overlap optimally. The goal of this study was to investigate specific regional effects in the seat, and not in the subjects' anatomical regions. As the pressure distribution mat is affixed to the seat, and the identical seat was used for all subjects, it is not reasonable to apply picture-transforming techniques.

b) *General linear model*

Comparably to Friston et al. (1994), the first step is to apply a general linear model that fits the pressure data X over time for every sensor point. A general linear model with $j = 1, \cdots, J$ sensor points and $i = 1, \cdots, I$ observations generally has the following form:

$$X_{ij} = g_{i1}ß_{1j} + g_{i2}ß_{2j} + \cdots + g_{iK}ß_{Kj} + e_{ij} \tag{1}$$

Where the coefficients g_{ik} are explanatory variables relating to the conditions under which each observation was made, β are the models linear parameters and the errors e_{ij} have to be independent and identically distributed [N(0,σ_j^2)] normally.

In this study, each observation $X_{i:}$ is a single SPDI with $J = 2304$ sensor points. For the explanatory variables $g_{i:}$, integer values indicated the level of the factors, which is described in more detail in equation (4).

Next, Equation 1 is transformed into matrix form as a multivariate general linear model:

$$X = G\beta + e \tag{2}$$

Here X is the data matrix with elements X_{ij},. Because the analysis included multiple subjects, the data matrices were concatenated along the observation dimension in the following form:

$$X = \left(x_{1_1} \cdots x_{n_m}\right) \tag{3}$$

Where $n = 3$ reflects the three different conditions (AC, PC, AC) and $m = 37$ the number of subjects. Because each condition of each subject included 4750 SPDIs with 2304 sensor points this resulted in a data matrix $X \in \mathbb{R}^{527250 \times 2304}$.

The next task was to formulate a design matrix G including the explanatory variables, which describe the experimental conditions: $n = 3$ for the three different conditions (AC, PC, AC) and $p = 4$ represents the baseline and the three different sequences of the MS. The baseline includes the resting time intervals, as well as the times within the massage program when none of the air bladders were inflated.

Because the subjects might have changed their body position between the conditions, a separate baseline vector was included for each condition. As a result, a design matrix G with size $527250\ x\ 12$ was generated. The design matrix G consists of a one-hot vector g_i encoding the current condition n and sequence p for each observation i.

$$G = \left(g_{1_1} \cdots g_{p_n}\right) \tag{4}$$

c) ß-Map

The next step is to calculate the least-square estimates of $\hat{\beta}$. Referring to Pataky (2010), these are calculated by:

$$\hat{\beta} = X^{+}Y \tag{5}$$

Where X^{+} is the Moore-Penrose pseudo-inverse of X. $\hat{\beta}$ is a matrix with size $12\ x\ 2304$, comprising 12 parameters for each sensor. At this point, it is useful to reshape and plot the $\hat{\beta}$-vectors of interest, as can be seen in part (A) and (B) in Figures 9, 11, 12. Because the size of the β-values is dependent on the correspondence and the change in pressure during the related sequence, they represent a qualitative overview, how the pressure distribution changes in the mean over all subjects.

d) Exclusion of unloaded sensors

As can be seen in the example provided by Figure 10 (A), some of the sensors were unloaded in each subject and each condition. If a sensor solely included ß-values below 0.01 for each condition, it is expected that the sensor only contains baseline noise and no relevant information. In our experiment, this was the case for 900 sensors. The related sensors were excluded from further analysis by replacing their β-values with NaNs. Figure 10 (B) shows a β-map after the process.

e) Contrast image

Referring to Friston et al. (1994), the next task is to calculate and visualize the difference between conditions by using linear compounds or contrasts of the parameter estimates $\hat{\beta}$. Therefore, a contrast vector c with size 12 x 1 was created, which was multiplied with $\hat{\beta}$ afterwards.

$$weighted\ \hat{\beta} = c\ *\ \hat{\beta} \tag{6}$$

The twelve elements of the contrast vector represent the baseline and the three different sequences within the conditions. For comparing two samples, a contrast vector such as in equation (7) can be used as an example. If this contrast vector was used in this study, one would compare the baseline of the first condition with that of the second.

$$c = (-1\,1\,0\,0\,\cdots) \tag{7}$$

The result is a vector named $weighted\ \hat{\beta}$ with size $1\ x\ 2304$. Reshaped into the original form, the resulting matrix is called contrast image.

f) t-Map

The next step is to make a statistical inference about the effects of interest. In order to conduct a generalized t-test, a t-map was created that contains one t-value for each sensor with the following formula (Pataky, 2010):

$$t_j = \frac{c^T \hat{\beta}_j}{\hat{\sigma}_j \sqrt{c^T (G^T G)^{-1} c}} \tag{8}$$

Where the nodal variance $\hat{\sigma}_j{}^2$ is estimated as:

$$\hat{\sigma}_j{}^2 = \frac{(\varepsilon^T \varepsilon)_{jj}}{J - rank(G)} \tag{9}$$

Where $(\varepsilon^T \varepsilon)_{jj}$ is the j^{th} element of the $(J \times J)$ sum of squares error matrix $\varepsilon^T \varepsilon$ and the errors degrees of freedom is J - $rank(G)$.

Errors ε , hence the residuals, can be obtained from the difference between the actual and estimated values of X:

$$\varepsilon = X - G * \hat{\beta} \tag{10}$$

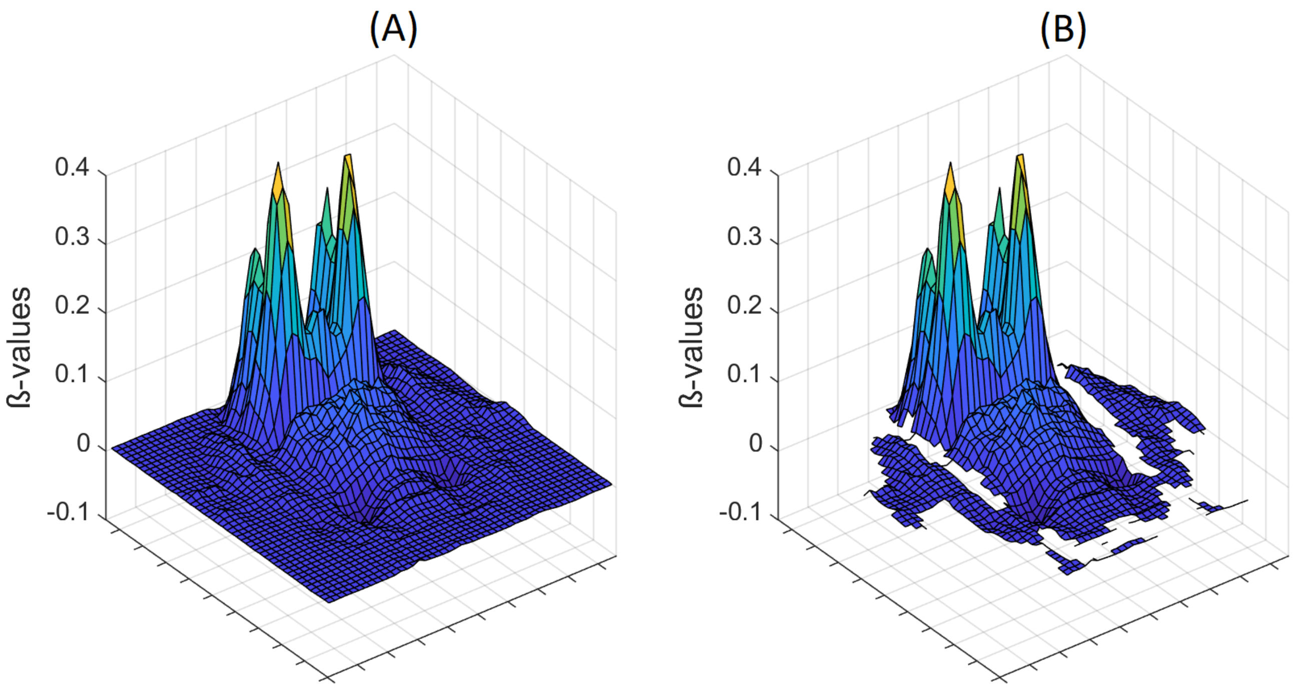

Figure 10: *The figure clarifies the exclusion of the unloaded sensors that comprise no information. (A) shows an exemplary ß-map before and (B) after the processing step. The exclusion line fits close to the body print. Occasionally even irrelevant sensors within relevant areas were ruled out. It was possible to reduce the sensors of interest from 2304 to 1404 sensors.*

Once reshaped and plotted into the original form (see Figure 11, 13, 14), the t-map allows to make inferences about the significance of the activation level for each sensor. Furthermore, t-values have a sign and show the direction of the effect. Generating one map, including the significance as well as the direction of effects, facilitates the identification of coherences within the whole sample.

g) p-Map

As the final step, p-values were calculated based on the t-values with degrees of freedom $m - 1$. In accordance with findings in the literature (Bogie, 2008; W. Li et al., 2009; X. Wang et al., 2006) the p-values were corrected for multiple comparison using False Discovery Rate correction (Groppe, 2020). With the p-values plotted as a p-map, it is now possible to define one or more sensors that fall below a given significance threshold or, as in this study, to examine which of the sensors show the lowest p-value. Since a very large number of sensor points showed p-values below the significance threshold of .05, the threshold was lowered in line with W. Li et al. (2009) until the remaining number of sensor points below the threshold formed a realistic sensor size.

5.6 Results

The analysis aimed to compare the pressure change between using the MS (1) with interaction and (2) without interaction. Accordingly, two ß-maps were created. The first ß-map reflects the sample's pressure change from the baseline to the periods during which the air bladders were inflated in the passive condition. The second ß-map also shows the change from the baseline to the periods when the air bladders were inflated, but in the active conditions. The contrast vector was weighted in such a form, that it reflects the comparison between the pressure changes in both conditions. That means, t-values above 0 show that the pressure increased more in the active conditions compared to the passive one, t-values below 0 reflect that pressure decreased more in the active conditions compared to the passive one. By means of the referring images, it was clearly possible to differentiate between the active and the passive conditions. For the lumbar sequence, pressure sensors should be placed just above the lumbar air bladders. For the shoulder sequence, however, they should be located directly on the shoulder air bladders. A more detailed description is given below. For a better interpretation of Figures 11, 13 and 14 in this chapter, it may be helpful to make a comparison to Figure 17 in Chapter 6, which schematically shows the sensor locations in relation to the air bladders.

5.6.1 Lumbar sequence

ß-Map

During the passive condition (Figure 11 A), increasing ß-values emerged around the lumbar air bladders. In contrast, above this area in the cranial direction, decreasing ß-values occurred. During the active conditions on the other hand, positive ß-values were found almost in the whole backrest, constantly decreasing from lower to the cranial part of the backrest (Figure 11 B). That means higher ß-values were found in the active conditions compared to the passive condition on - as well as cranial to the air bladders.

The area cranial to the air bladders additionally showed reversed magnitudes of the ß-values during the passive compared to the active condition.

t-Map

Positive t-values occurred dispersed over a large area in the seat back, visualized in Figure 11 C. The highest t-values were observable on and just cranial to the lumbar air bladders. Above this region with high t-values, a decreasing height of t-values was found in the cranial direction, merging into indifferent t-values in the shoulder region.

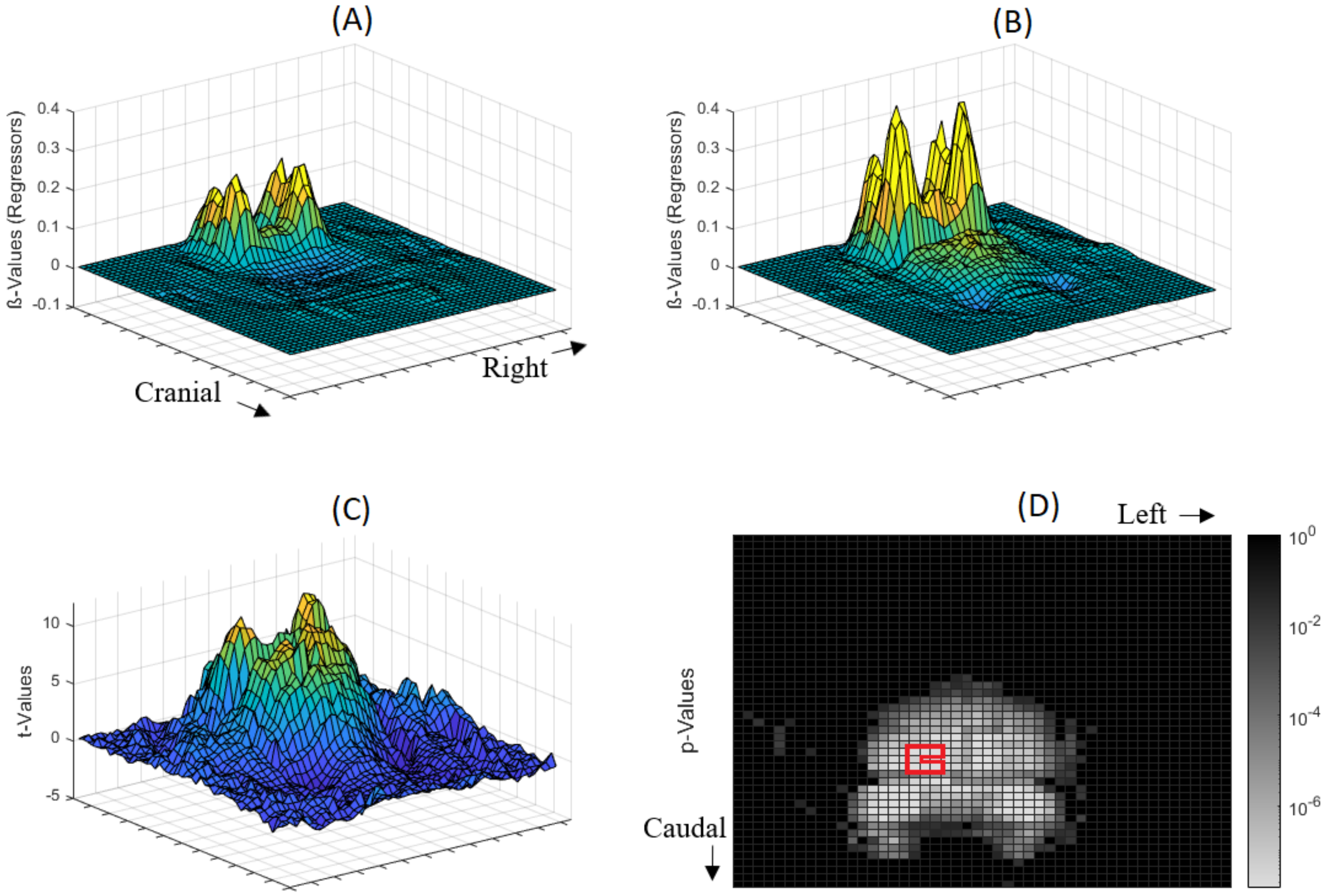

Figure 11: *Resulting maps for the lumbar sequence including ß-Maps during the passive (A) and active (B) conditions and the referring t-Map (C) and p-Map (D). For a better visualization (A) - (C) were rotated around 180 degrees and unloaded sensors were not excluded as described in Chapter 5.4. The exclusion of sensors for the statistical analysis remained unaffected. The seven sensor points with the lowest p-values are outlined in red in (D).*

p-Map

As can be seen in Figure 11 D, numerous sensor points showed highly significant differences between the pressure changes in both conditions. In order to demarcate an area that correlates to the likely size of a possible sensor, the alpha limit was set up to 2 x 10^{-8}, resulting in seven sensor points that were the most significant. The sensor points were located in the area just above the lumbar air bladders.

Pressure Curve

In order to finish the evaluation study, the pressure values from the seven most significant sensor points were summed into a single value and a mean value was calculated across all subjects. The resulting pressure curves were smoothed for the passive and the active conditions using a moving average with a span of 20 samples and plotted into Figure 12. The blue line represents the pressure during the passive condition and the red line shows the mean in pressure of both active conditions. The grey areas represent the intervals when the air bladders were inflated during the lumbar sequence. Each curve for every subject was also plotted separately, disclosing that seven subjects showed no systematic change in amplitude

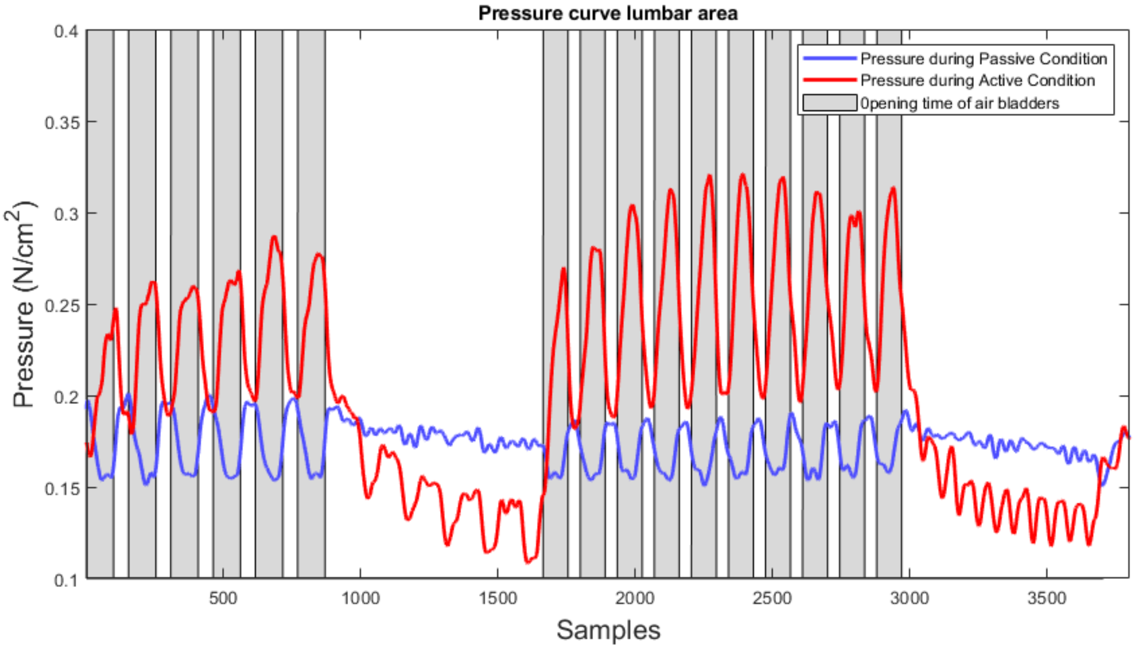

Figure 12: *The figure shows the sample's mean signal curves for the seven most significant sensor for the lumbar sequence. Pressure values decreased during the passive condition when the air bladders inflated (blue curve). During the active condition, while subjects interacted with the system, increasing pressure values occurred (red curve).*

during the passive conditions whereas all other subjects showed a decreasing amplitude when the air bladders were inflated. Only two subjects revealed no systematic change and thus increasing amplitudes during the active conditions. However, these plots would exceed the scope of this thesis and are not included here.

5.6.2 Shoulder sequences

Both the left and the right shoulder sequence showed very similar results. Therefore, the following paragraph summarizes the results of both sequences together.

ß-Map

As can be seen in Figure 13 A and Figure 14 A, the shoulder sequences during the passive condition showed no global change of ß-values. Instead, increasing ß-values were only observable directly on the

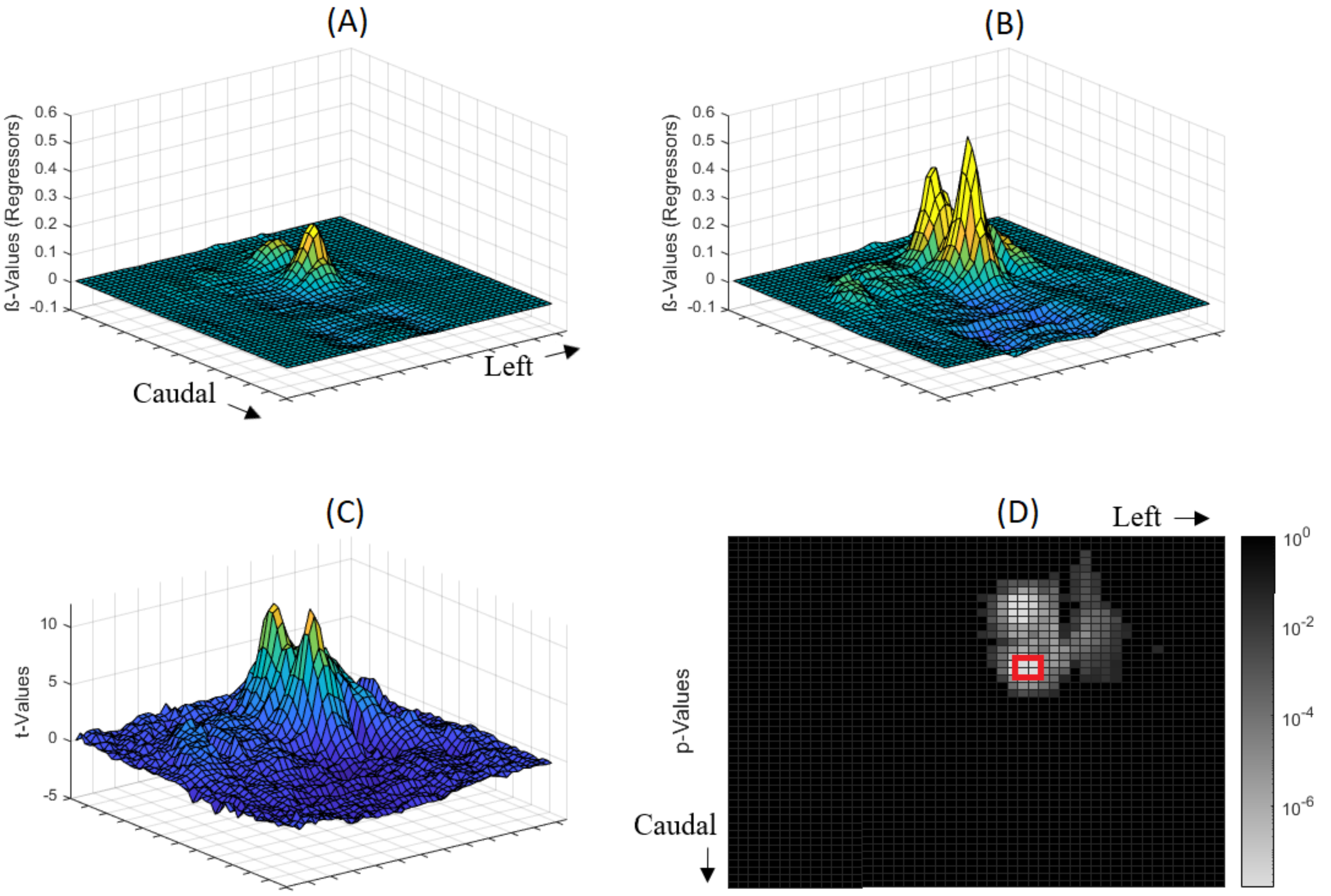

Figure 13: *Resulting Maps for the left shoulder sequence. Lettering refer to the same Maps as in Fig. 9. The four sensor points with the lowest p-values are outlined in red in (D).*

shoulder air bladders with substantially higher ß-values over the more caudal ones. The ß-maps for the active conditions illustrated in Figure 13 B and Figure 14 B form a very similar shape as in the passive condition but with considerably higher ß-values. That means, ß-values over both the cranial and the caudal shoulder air bladders were higher in the active conditions compared to the passive condition whereby the ratio of change was higher for the more cranial air bladders. In detail, the ß-values just lateral to the air bladders also showed a small increase from the passive to the active conditions, whereas the ß-values further caudal to the shoulder area decreased slightly.

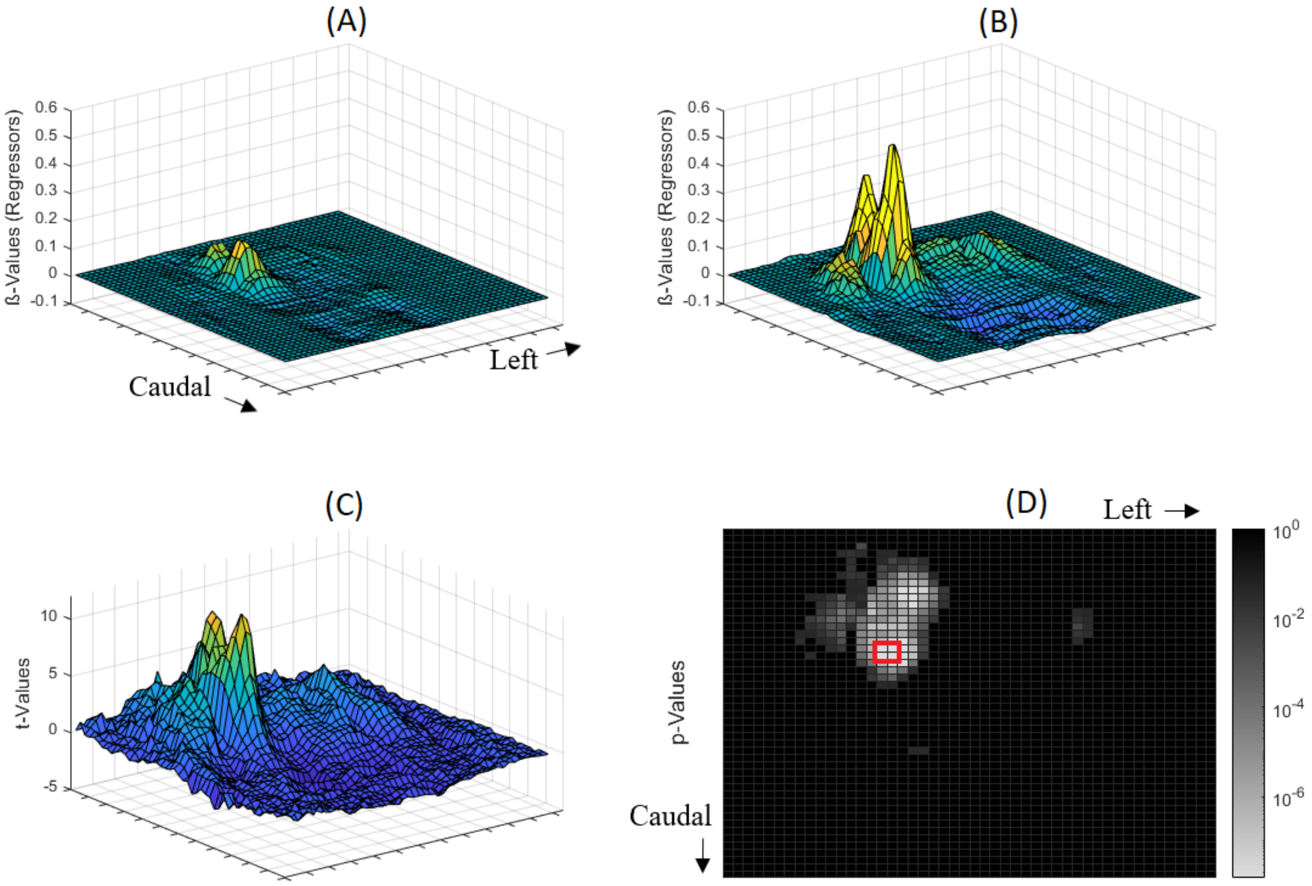

Figure 14: *Resulting Maps for the right shoulder sequence. Lettering refer to the same Maps as in Fig. 9. The four sensor points with the lowest p-values are outlined in red in (D).*

t-Map

The highest t-values were observable directly on the air bladders, with a positive sign and a small difference of amplitude between both air bladders (Figure 13 C and Figure 14 C). Negative t-values, though with small amplitudes, occurred in the lumbar region.

p-Map

Referring to Figure 13 D and Figure 14 D, significant differences were observable directly on the shoulder air bladders. P-values on the cranial air bladders were marginally lower, compared to the more caudal air bladders. In both cases, however, the p-values are very low, consequently it is to be expected that the difference between the p-values has no relevance in practice. Therefore, it is reasonable to place the pressure sensors either on the cranial or caudal shoulder air bladders. It was decided to use the caudal air bladders to increase the likelihood that the IASS would be suitable for individuals smaller than the 5th percentile for women (e.g. children), who may not be able to reach the cranial air bladder.

Thus, the alpha-limit was set up to 10^{-7} for the right shoulder and 3×10^{-8} for the left shoulder, resulting in four most significant sensor points for each side on the lower air bladders.

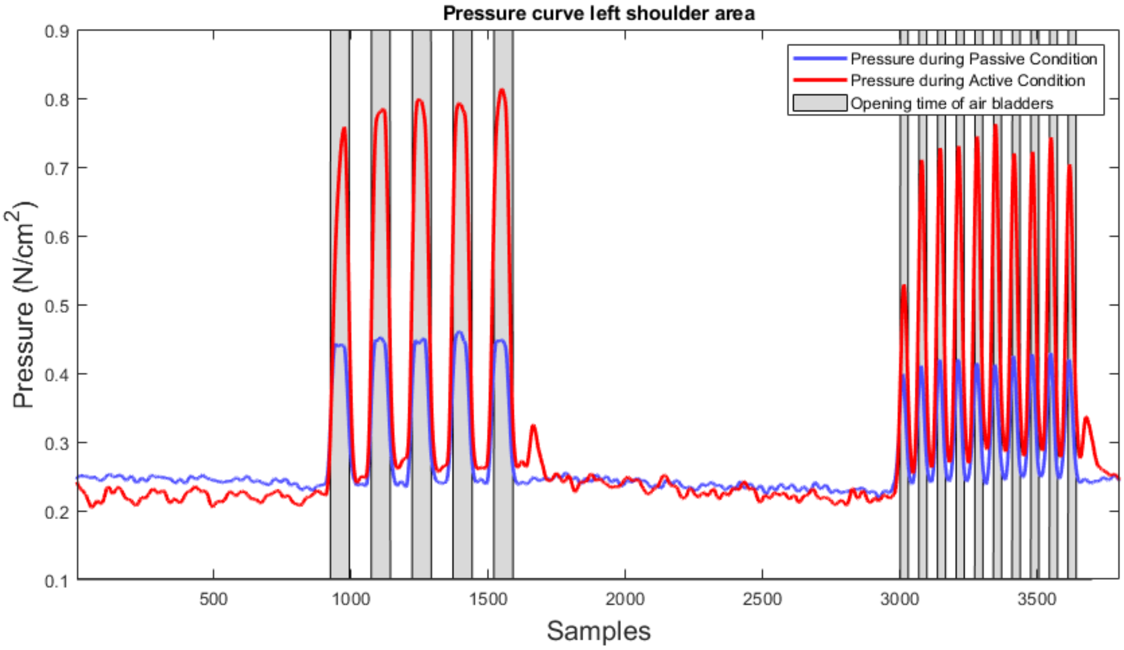

Figure 15: *Signal curves for the three most significant sensor points for the left shoulder area. Pressure values during the active condition were considerably higher compared to the passive condition.*

Pressure Curve

The same steps, as explained for the lumbar sequence were applied to the four chosen sensor points for both sides. Figure 15 and 16 show the resulting pressure curves for the left and the right shoulder. Both sensor locations recorded considerably smaller pressure amplitudes during the passive compared to the active condition.

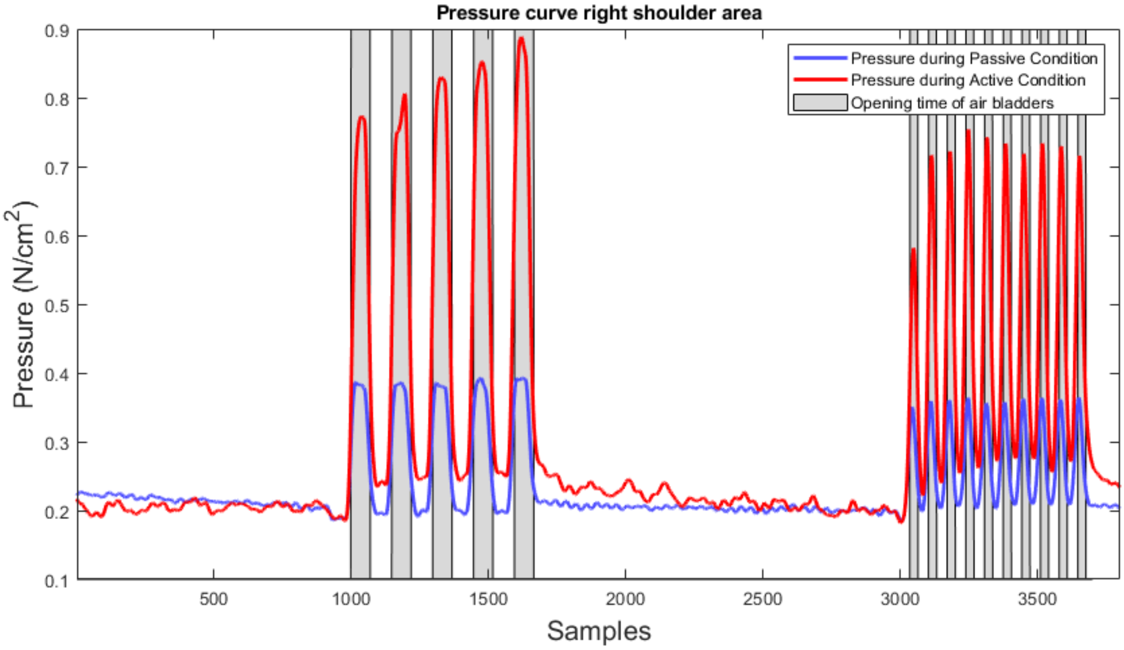

Figure 16: *Signal curves for the three most significant sensor points for the right shoulder area. Equivalent to the left shoulder area, pressure amplitudes are clearly higher during the active condition.*

5.7 Discussion

5.7.1 Sensor locations

The study was able to identify regions in the seat back that showed highly significant different pressure changes in the active conditions compared to the passive condition. Before conducting the study, it was decided, that the IASS should use three individual sensors in the seat back to distinguish interaction and no interaction. To increase the likelihood of a reliable detection between both states, sensors should be placed in those locations that show the highest significance between the pressure change from the baseline to the active condition and the pressure change from the baseline to the passive condition. For the shoulder sequences, the study exposed local and highly significant different pressure values between the passive and the active conditions in the shoulder area. Consequently, it is suggested to position the sensors with a small detection surface directly on the shoulder air bladders. In this way, the sensor surface is limited to the area where the best data can be collected to distinguish between the two conditions. For the lumbar sequence, highly significant pressure differences between the passive and active conditions were found as well. However, for the lumbar sequence, the best sensor positions were not located directly on the lumbar air bladders but just above them. The pressure values in these areas not only differed highly significantly, but also showed opposite pressure amplitudes between the two conditions. This confirms the assumption from Chapter 5.2, that placing the sensors directly on the air bladders is not necessarily optimal, as the air bladders exert pressure against the passenger also without interaction. In comparison with the shoulder region, the significant areas in the lumbar region were much more distributed. Nevertheless, with the selection of seven sensors, corresponding to an area of 11.3 cm^2, it was possible to define locations that allowed to detect highly significant pressure differences between both conditions. If the minimum size of the sensor is less important, a larger detection surface might further improve the classification performance. In this way, the data might also be less sensitive to disturbing effects, especially during driving.

5.7.2 Statistical Parametric Mapping

The study revealed manifold alterations of pressure in the seat. A precondition for these findings was the high resolution that SPM offers in comparison to the three conventional methods that were listed in Chapter 5.2.2. A visual inspection for distinct features by the examiner would simply not have been possible due to the large number of SPDIs. As described by Pataky et al. (2008), a calculation of single parameters for the entire seat surface, but also for areas of a body map, can lead to a neutralization of effects. If some areas show increased and others decreased pressures, the total pressure over both areas may remain unchanged. However, even if pressure changes are detected, they refer to the entire seat surface or, in the case of body maps, at least to large-area parts of the body, and thus do not allow any or only a limited conclusion to be drawn about local changes. The central idea of conventional methods is to reduce the amount of data by subsampling. Therefore, any approach to increase the number of areas of a map to improve the resolution would be contradictory, since it leads to a larger amount of data. As it has been shown in previous studies that the use of conventional methods can be problematic (Pataky et al., 2008), it was decided not to compare conventional methods and SPM again with the data of this study, as it would be beyond the scope of this work.

Another advantage of SPM is that the exclusion of unloaded sensors to reduce redundant processing capacity and statistical comparisons can be easily integrated into the evaluation. With the applied interim step, it was possible to exclude each unloaded sensor separately, enabling that the cut off fitted closely to the pressure distribution of the sample.

In principle, it would have been possible to include other factors in the model, which influence the pressure distribution. These include, for example: seat back and seat pan angle (X. Wang et al., 2019), weight (Paul et al., 2012), stature (Kyung & Nussbaum, 2008; Paul et al., 2012), gender (Vos et al., 2006), posture (Moes, 2007) and age of the subject (Kyung & Nussbaum, 2013). The inclusion of these factors can be useful for some research questions, such as investigating the relation between pressure distribution and discomfort. For this study, however, the author deliberately chose not to include these factors. In order to be able to transfer the results of the study to the algorithm of the IASS, the model in the study must be based on the same information that will later be available in the vehicle. In the future, it might be possible that some of the influencing factors could be captured using other sensor systems in the vehicle (e.g. camera systems). However, it is preferable not to rely on this development and to develop the IASS independently of additional sensor systems. The inclusion of the additional factors would certainly have led to a better fit of the pressure data, but the model would have been based on data that will not be available later. Therefore, in this investigation, the focus was to find sensor locations that are valid for the whole sample even under random influence of these variables.

5.7.2.1 Normal distribution

The residuals of the model in our study were not normally distributed, which is, in a conservative view, an assumption to use parametric tests in statistics. Therefore, the pressure distributions were smoothed on a trial basis with Gaussian kernels, as described in Friston et al. (1994). Afterwards the general linear model was applied. However, this had little effect on the distribution of the residuals. The reason for the lack of normal distribution could be that the sample consisted of both men and women. Because, as mentioned by Vos et al. (2006), men show on average higher pressure values than women. However, the distribution was still very symmetrical and the t-test is often described to be robust against a violation of a normal distribution (Lumley et al., 2002). Therefore, SPM was nevertheless considered to be an appropriate statistical method for the underlying dataset. If future datasets show more skewed distributions or only narrow significant differences are found, non-parametric methods exist, that can still consider the entire pressure distribution. Particularly mentioned are permutation tests (Helwig, 2019; Nichols & Holmes, 2002; Winkler et al., 2014).

5.7.2.2 Multiple comparisons correction

Since 1404 statistical comparisons were conducted, false discovery rate was used to control the familywise type I error. This correction was used because it is less conservative than Bonferroni correction. However, also the False Discovery Rate, just like the Bonferroni method, ignores the spatiality of the p-maps. Using such correction methods that ignore the spatiality is valid, but leads to a conservative correction (Pataky, 2008, 2010). The reason is, that these methods consider the sensor points as independent. However, it can be assumed that the sensor points are spatially correlated and therefore not independent. As a result, the values should actually be corrected less than with the False Discovery Rate or Bonferroni correction. However, the p-values in this study were so low that significant differences appeared for a large number of sensor points even after correction with false discovery rate. From these sensor points, those were picked out with the lowest p-values to define the best sensor locations. Accordingly, choosing a different correction method would not have changed the practical conclusions of this study. However, if future studies require more sensitivity, methods based on Random Field Theory might be applied (Brett et al., 2004; Pataky, 2008).

5.8 Limitations

Although the study was conducted in a production vehicle with realistic dimensions, the results cannot be transferred to a driving situation without limitations. For example, real driving might require additional visual demands that might influence posture. If the IASS would not work properly based on the information that was collected through this study, it might be useful to conduct a second study in which subjects are actually driving. In a driving study, influential factors (e.g. acceleration force), can be added to the model to manifest their influence on the pressure data.

In addition, a larger sample might be useful to improve generalization of the results as well as to account for greater anthropometric variability. The sitting height had a good distribution across the sample (see Figure 8). However, a sample of 37 subjects is not sufficient to represent all anthropometric variability. Most remarkably, Figure 8 shows, that the range around the 5th percentile for females is represented by only one subject whose seat height was 80 cm. There is also a gap in the distribution around the seat height of 95 cm. These gaps could limit the generalizability of the study's findings. To increase the generalizability of the results, future studies should include a larger sample that provides better coverage of anthropometric variability.

5.9 Conclusion

By applying Statistical Parametric Mapping (SPM) to seat pressure distributions, it was possible to define sensor locations in the seat back, where the pressure data differed significantly depending on whether the subjects' interacted with the IASS or not. In the process, SPM has proven to be a suitable and intuitive option for the analysis of seat pressure distributions. Traditional analysis methods merge multiple sensor points together, making it impossible to examine locally dependent effects. However, such localized information was necessary to define optimal pressure sensor locations with high spatial resolution in the seat back. Introducing SPM in the analysis made it possible to break down the large number of SPDI without losing information about the location of effects.

The successful application of SPM to seat pressure distribution images in this study suggests that the use of SPM may also be beneficial in other research areas where seat pressure distributions are captured. Studies evaluating seating discomfort are a prominent example (e.g. Gyi & Porter, 1999; Kyung & Nussbaum, 2008; Porter et al., 2003). To achieve enough sensitivity future studies could aim for a multiple comparison correction that takes spatial correlation into account.

6. Realization of the interactive seating prototype

This chapter describes the setup of the IASS, based on the information from Chapters 4 and 5. The study from Chapter 5 was conducted to determine the sensor locations in the seat. However, at this stage, the study has only provided information on which sensors of the mat provide the best information. Although, the significant areas were described in relation to the air bladders for better comprehensibility in Chapter 5, this relation was visually estimated, which is not accurate enough for building up the prototype. In the study, SPM was used to analyze the data with high spatial resolution. This accurate information can only be preserved when the relevant sensor points are brought into exact spatial reference to the seat.

Therefore, the seat was scanned while the pressure distribution mat was still attached. After a seat model specific calibration, the scanning machine displays the location of the sensor points in reference to the seat in form of CAD coordinates to an accuracy of one tenth of a millimeter. Due to confidentiality, an exact illustration cannot be shown, but Figure 17 schematically shows the CAD model of the massage element in the backrest and the sensor locations which are marked with orange dots.

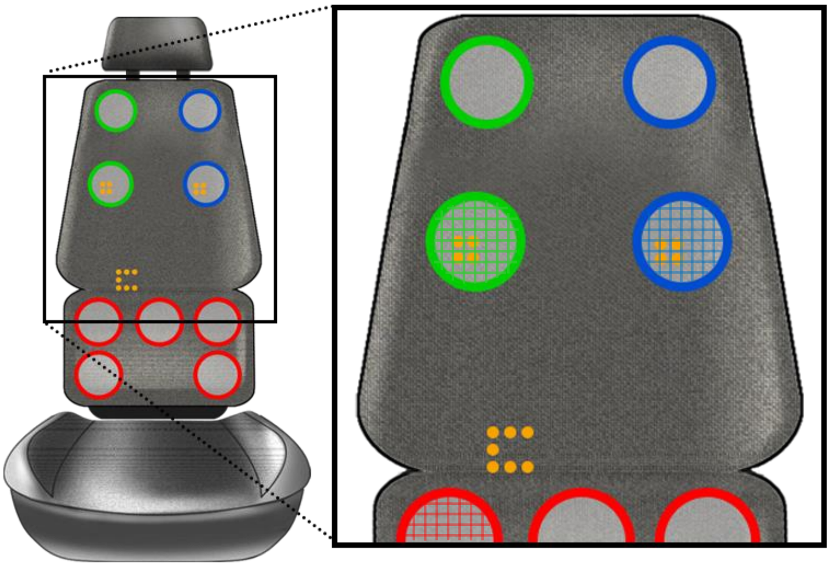

Figure 17: *Schematical illustration of the CAD model of the massage element and the sensor locations in the backrest. Air bladders used for the right shoulder sequence are marked in green, for the left shoulder sequence in blue and for the lumbar sequence in red. Sensor locations that were defined in Study I are marked with orange dots. The air bladders whose pressure was measured for detection are shaded in the color of the corresponding sequence in the magnified part of the image.*

On this basis, different types of sensors were tested for the prototype. Among those, air pressure sensors (NXP® Seminconductors MPX4250AP) that measure the pressure inside the seat bladders turned out to be the best choice as they delivered the most stable signal. For a later series integration these sensors have the additional advantage that they do not have to be integrated directly into the seat surface. Consequently, the sensors are not mechanically stressed by the passenger, which is very likely to increase their durability. For the shoulder sequences, the air pressures inside the lower shoulder air bladders (shaded in blue and green) were recorded. For the lumbar sequence, the upper lumbar air bladder on the right from the passenger's view (shaded with red) was used. The position of the air bladder is close to, but not exactly within, the area evaluated in Chapter 5 as the optimal sensor position for the lumbar sequence. In addition to the air bladders used for massage, high-quality seats also include air bladders for the multicontour adjustment. Some of these multicontour air bladders form the lumbar support. Later testing had shown that measuring the pressure inside the lumbar support is optimal, because the air bladders used for it are located directly in the area of the optimal sensor location. However, this had not yet been implemented in the prototype used for the two evaluation studies in this thesis due to time constraints. Nevertheless, the system worked also well with the use of the massage bladders.

The main program of the IASS consisted of a script in Mathworks® Matlab® R2018b that directly communicated with a microcontroller (Arduino Mega). The microcontroller read out the pressure sensors and controlled the LED stripes (Adafruit Neopixel RGBW) as well as the four vibration motors in the seat cushion (Mercedes-Benz 223 series). The user interfaces were realized in Matlab as well. Both the LED stripes and the vibrators were supplied with external power.

Chapter 5 revealed that the pressure in the area of the shoulder air bladders also increases if the passenger does not interact with the seat. Therefore, it is advantageous to perform a calibration measurement before using the IASS. During this calibration measurement, the MS is started, but the passenger is instructed not to interact with the system. During the calibration measurement, the pressure values inside the air bladders are recorded. This allows measuring the pressure increase without interaction. Afterwards, these pressure values are multiplied with a predetermined factor in order to determine a threshold value. The user must now exceed this threshold for a movement to be classified as an interaction.

7. Study II – Passive driver fatigue in the driving simulator

This chapter was published in a largely similar form in Lampe & Deml (2022b).

7.1 Introduction and Abstract

This chapter reports a study that compared the use of the IASS with a state-of-the-art massage seating system and a control condition in a 40-minute simulator ride (N = 35).

The primary objective of the study was to compare the seating systems regarding their efficacy against passive driver fatigue in a monotonous driving situation. For the evaluation, subjective fatigue, lane keeping ability and eye tracking data were captured. In addition, heart rate, heart rate variability and skin conductance were measured.

The IASS, which is described in more detail in Chapter 4, represents a secondary motor task. The MS, on the other hand, induces only tactile stimuli. Thus, this was the first study to investigate whether a secondary motor task in form of an IASS can generally have a positive influence on passive driver fatigue. In addition, the effect of a seating system that induces a secondary motor task was compared for the first time with a seating system that uses additional task-independent stimuli (see Chapter 2.5.2).

The second objective was to compare the overall user experience of both seating systems. This aspect is of interest, as a good user experience is associated with a higher probability of the systems being used regularly. For this, the seating systems were rated in terms of user experience, emotional perception as well as comfort and discomfort.

As a third objective, the influence of the seating systems on workload and task complexitiy was measured with questionnaires and eye tracking. In Chapter 2.2.3.3 a model was presented that aims at explaining the influence of monotony and task complexity on workload and therefore on task performance. Therefore, it was of interest, if the theoretical model is in line with the observations in this study.

The core contribution of this study is to investigate whether the IASS can be an additional or even better measure against PDF compared to the current state of research.

Results: The assessment of subjective fatigue and lane keeping showed that the use of the IASS resulted in a significant improvement of PDF compared to the massage and control condition. The activating effect of the IASS was also reflected by an increased heart rate and skin conductance. However, it remains open, to what extent the effect on both parameters is caused by reduced passive driver fatigue and/or increased physical activity and task complexity. The alerting effects of the IASS were also reflected by an increased eyelid distance. However, blink frequency and duration as well as heart rate variability showed no clear patterns of fatigue over time in any of the conditions. Thus, all three parameters seemed not be suitable to capture passive driver fatigue in this study. Regarding the user experience and emotional perception, the use of the IASS was clearly preferred over the massage seating system. In addition, the IASS was superior in improving comfort and discomfort. Regarding workload, only small effects were measured. Therefore, the study showed a tendency to support the model of Chapter 2.2.3.3. However, the results are not clear enough for a definite contribution.

Conclusion: In this study, the interactive seating system showed a strong potential as an effective measure to reduce passive driver fatigue during monotonous driving situations. In addition, the users preferred the IASS over the MS in terms of user experience as well as sitting comfort and discomfort.

7.2 Material and Methods

7.2.1 Setup

7.2.1.1 Simulator

Figure 18 shows the measurement setup. The driving simulator included three screens (LG 65LA9659 – ZA; screen diagonal 65 inch; resolution 3840 x 2160). However, during the ride, only the main screen in the center displayed the track.

Before the actual conditions, a training set for the IASS was included in the study procedure (see Chapter 7.2.3). During this training set, a user interface was shown on the right screen to give assistance in learning the movement task (see Figure 19). On the left side of the user interface, illustrations of the target movements were shown. On the right side, a bar plot showed the current pressure value and a threshold line which had to be exceeded by pushing against the air bladder. During the actual conditions, the user interface disappeared which made the use of the IASS suitable while driving. The vehicle was controlled by a steering wheel, a brake and accelerator pedal (Fanatec Club Sport Wheel Base, Fanatec Club Sport Steering Formular Carbon, Club Sport Pedals V3). The seat was mounted on a motion base, which generated movements according to the driving dynamics and vibrations from the road. The movements were realized with the motion system DBOX 4250C. The multicontour seat was freely adjustably. Loudspeakers played the driving sounds (Logitech Z906). The simulation software was IPG CarMaker 7.0.3 which recorded at a sampling rate of 100 Hz. The subject was separated from the investigator by a visual shield to avoid interaction.

Figure 18: *Illustration of the measurement setup.*

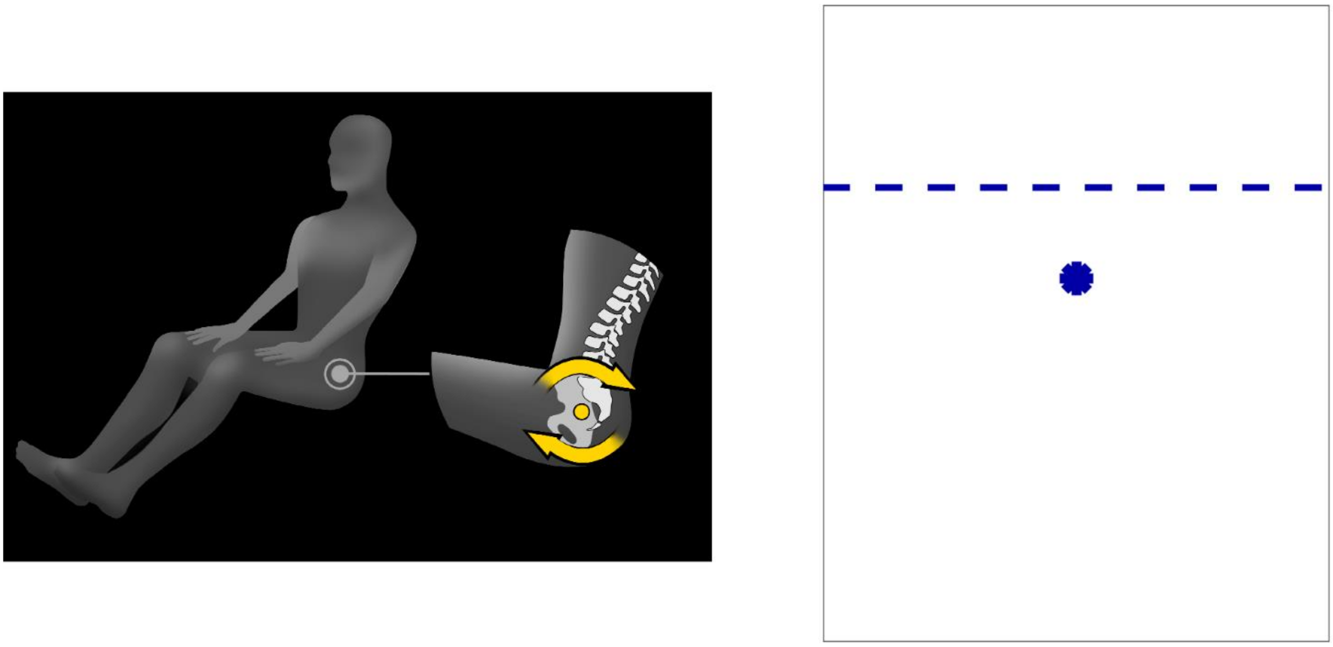

Figure 19: *User interface of the interactive seating system. On the left side, illustrations of the target movements are shown. On the right side, a bar plot shows the current pressure value (dot) of the target air bladder and a user-specific pressure threshold (dotted line) that was determine with a calibration measurement (see Chapter 6). The dot should now be moved above the line by pressing against the currently inflated air bladder. As long as the dot was held above the line, the user received feedback via the vibrating elements and LEDs.*

7.2.1.2 Route Design

To the best of the author's knowledge, no precise definition of a monotonous driving route exists. Therefore, there is also no standardized specification available regarding the route design. In order to achieve the goal of producing PDF under the most realistic conditions possible, the specification of Bier et al. (2019) was followed as far as possible. Based on a literature review, Bier et al. (2019) have provided guidance on the design of monotonous simulator routes. In the present study, a three-lane circuit track was used. The table in Appendix B lists the characteristics of the route design in detail. The simulated vehicle was a Mercedes-Benz C350e (W205). Figure 20 shows an exemplary situation during the ride.

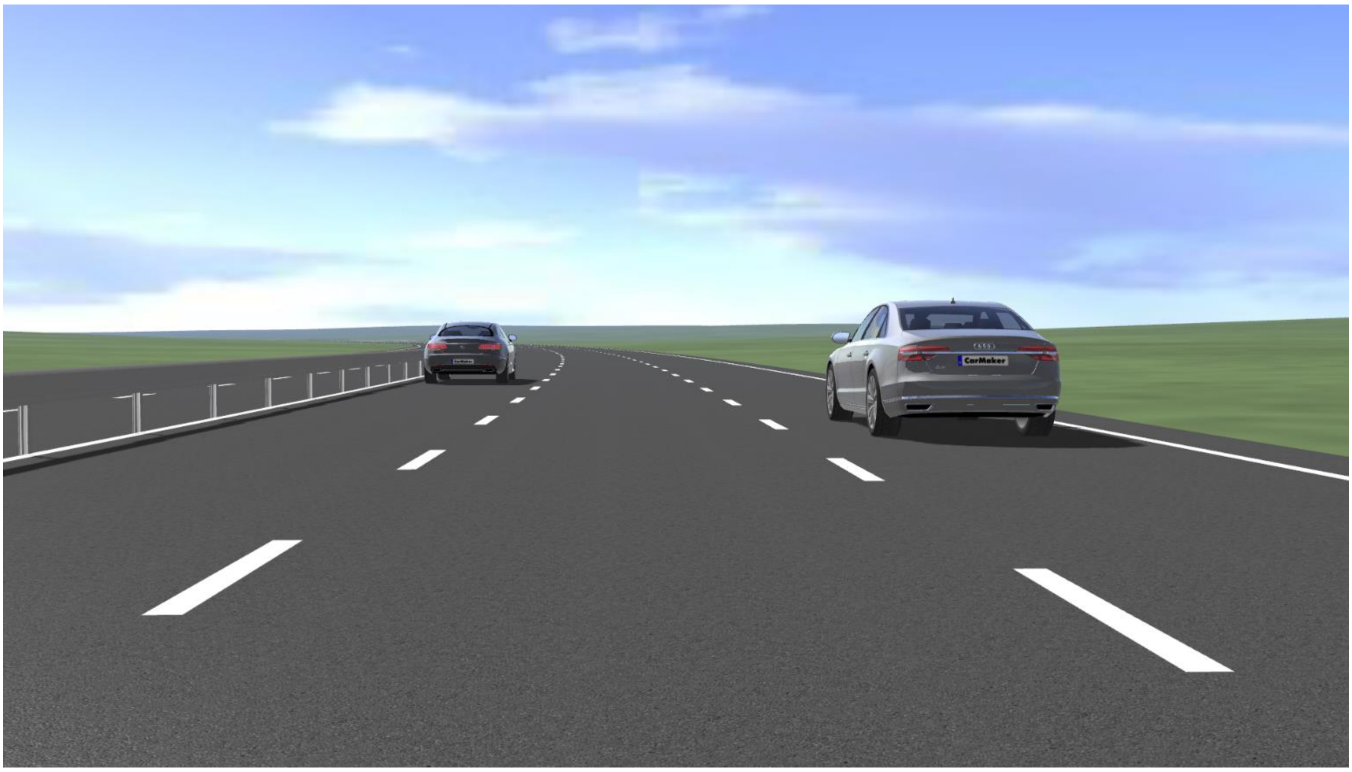

Figure 20: *Illustration of the route.*

7.2.1.3 Measuring devices

Eyetracking

A Smarteye Pro 6 eye tracking system was used. The system includes two Basler gigE cameras, each equipped with an infrared flash. The eye data was collected with a sampling frequency of 60 Hz.

Vital parameters

The vital parameters were recorded with a biofeedback device (Becker Meditec VARIOPORT-B). Electrodes for electrocardiography (ECG) were attached following the MC5 lead (Hamm & Willems, 2014): reference electrode on the xiphoid process of the sternum, positive electrode on the manubrium of the sternum, negative electrode in the area of the fifth intercostal space on the anterior axillary line. Electrodes for measuring skin conductance level (SCL) were placed at the medial side of the right feet at the anterior area of the ossa tarsi. The skin was not specifically prepared, e.g. cleaning with alcohol as such procedures can change the natural resistive/conductive properties of the skin (M. E. Dawson et al., 2007). In order to reduce movement artefacts, Ag/AgCl ECG-electrodes with decentralized press buttons were used for both the measurement of ECG and SCL. The vital data was collected with a sampling frequency of 256 Hz.

7.2.2 Measures

7.2.2.1 Questionnaires

The first part of the questionnaires asked for overall user experience: passive driver fatigue, sitting comfort and discomfort as well as emotional perception. The second part queried the level of workload.

Passive driver fatigue

From the author's literature, the Karolinska Sleepiness Scale is the most commonly used questionnaire to capture passive driver fatigue (e.g. Bier et al., 2019; E. Schmidt et al., 2017; E. Schmidt & Bullinger, 2019; Schneider et al., 2021).

Therefore, a German translation of the Karolinska sleepiness scale (KSS) was collected. The KSS ranges from (1) ‘extremely alert’ – (9) ‘very sleepy, great effort to keep awake, fighting sleep’, with labels on each step (Miley et al., 2016). For an overview of questionnaires to assess passive driver fatigue, please refer to Chapter 2.4.1.

Sitting comfort and discomfort

For the assessment of comfort and discomfort a German translation of an adapted version of the Chair evaluation checklist (Helander & Zhang, 1997) was used. The following statements for discomfort and comfort had to be rated with items ranging from (1) ‘not at all’ to (9) ‘extremely’:

Discomfort: (1) ‘I have sore muscles’; (2) ‘I have heavy legs’; (3) ‘I feel uneven pressure from seat pan or seat back’; (4) ‘I feel stiff’; (5) ‘I feel restless’; (6) ‘I feel tired’

Comfort: (1) ‘I feel relaxed’; (2) ‘I feel refreshed’; (3) ‘The seat feels soft’; (4) ‘The seat is spacious’; (5) ‘I like the seat’

The initial version of the questionnaire also includes the statement ‘The chair looks nice’ for comfort. Since the same seat with the identical look was used in all conditions, the questionnaire did not include this statement. For an overview of questionnaires to assess sitting comfort, please refer to Chapter 3.3.2.

Emotional Perception

An important part of user experience is the emotional perception of a product, which was queried with emocards that were originally used for the evaluation of cell phone designs (Desmet et al., 2001). Later, these were proposed by Kolich (2008) for the evaluation of car seats and finally used for this purpose by Franz, Kamp, et al. (2011) and Kamp (2012). The rating is made with a non-verbal self-report on the basis of the circumplex of affect by Russell (1980). The questionnaire includes 16 emocards, which are arranged at eight distinct places on a circumplex. The emocards show eight emotions, each represented by a female and a male face. The circumplex is based on two dimensions, 'pleasantness' in horizontal and 'arousal' in vertical direction. Figure 21 shows, how the emotions were presented to the respondents. For a more detailed illustration please refer to Chapter 7.3.1 in which a larger figure is shown with verbal explanations for each emotion. The subjects were asked to choose the face that best fits their emotional perception.

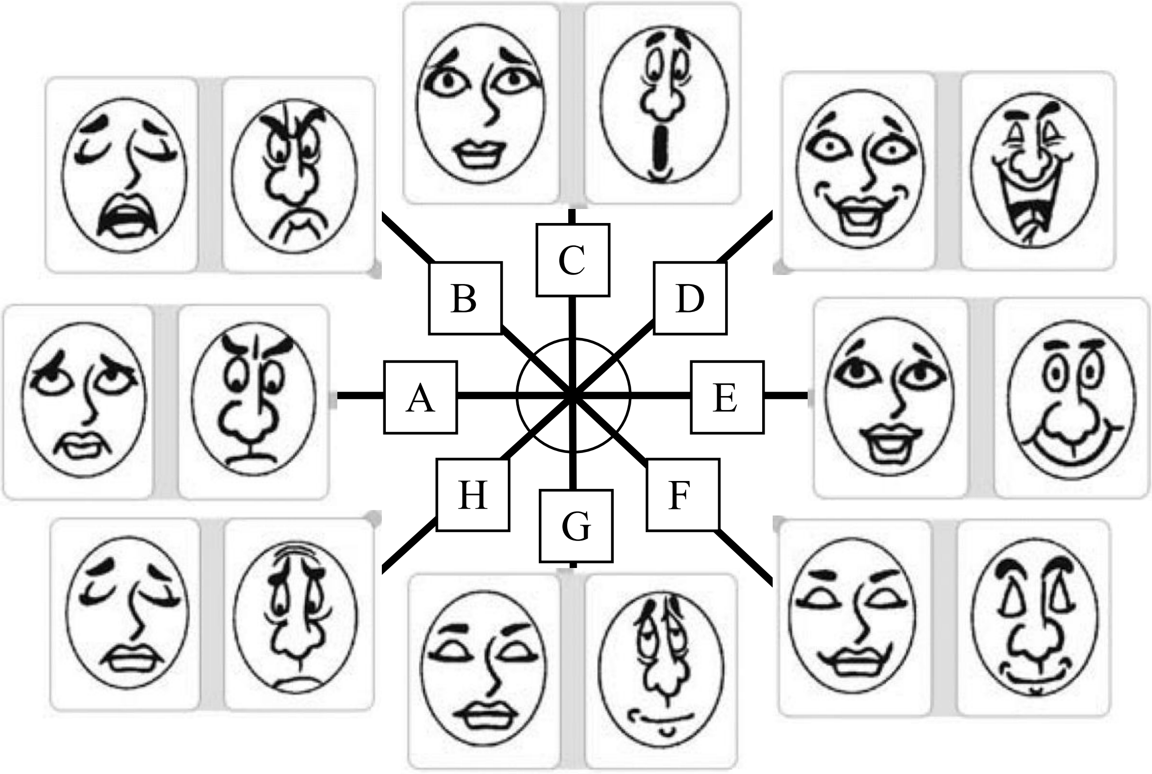

Figure 21: *Illustration how the emocards were presented to the subjects. The emocards were adopted from Desmet et al. (2001).*

Workload

In general, according to Cegarra & Chevalier (2008), three categories for the assessment of workload exist: performance measures (e.g. dual-task paradigm), physiological measures (e.g. heart and eye measures) and subjective measures (e.g. rating scales). The subjective assessment of workload with questionnaires in addition to performance measures is important because operators can react differently to increased task complexity. They may adjust their behavior, or accept lower performance (Pauzié, 2008).

Increased workload would not be detectable with performance measures in the first case and not with questionnaires or physiological measures in the second. Therefore, it is recommended to combine all methods. In this study, the DALI questionnaire was used to measure the subjective perception of workload (Pauzié, 2008, 2014). The DALI questionnaire is a modified form of the NASA-TLX questionnaire (Hart, 2006) consisting of seven factors adapted to the driving context. There is a reduced version of the NASA-TLX, without prior weighting of the factors, called the RAW-TLX. The elimination of the weighting only marginally affects the results and the collection is much faster (Hart, 2006). Likewise, no weighting of the factors was applied for the DALI-questionnaire in this study. The layout of the questionnaire was designed equivalent to the NASA-TLX. A brief explanation was included for each factor, to clarify their meaning for the respondents. Since the author is not aware of any publication which includes such explanations, these were formulated on the basis of the descriptions in Pauzié (2008). The questionnaire was German with a scale of (0) 'low' – (20) 'high'. The items were the following:

1. Effort of attention (How high was the required attention for the driving task? i.e. to think about, to decide, to choose, to look for, …)
2. Visual demand (How high was the visual demand necessary for the driving task?)
3. Auditory demand (How high was the auditory demand necessary for the driving task?)
4. Tactile demand (How high was the tactile demand necessary for the driving task?)
5. Temporal demand (How much time pressure did you feel in terms of the frequency or pace at which tasks or task elements occurred? Was the sequence slow and unhurried or fast and hectic?)
6. Interference (How strong were the distractions during the driving task? e.g. through additional tasks)

7. Situational stress (How high was the stress level during the driving task? e.g. fatigue, insecure feeling, irritation, discouragement, …)

User experience

The user experience was surveyed with rating scales. Since the questions related specifically to the seating systems these were only queried after the active and passive condition. All questions should be answered on a 6-point scale comprising the items: (1) ‘barely’, (2) ‘slightly’, (3) ‘to some degree’, (4) ‘considerably’, (5) ‘mostly’ and (6) ‘completely’. The questions were the following:

1. Does the seating system have a positive influence on your well-being?
2. Did the seating system activate you?
3. Did the seating system relax you?
4. Was the seating system fun?
5. Was the seating system exhausting?
6. Do you consider the seating system to be useful?
7. Does the system excite you?

With two additional questions, the participants rated the consumer acceptance of both seating systems on a 4-point scale with (1) ‘do not agree at all’, (2) ‘rather disagree’, (3) ‘rather agree’ and (4) ‘fully agree’. The statements were:

1. I would use the [seating system][5] regularly.
2. I would buy the [seating system] as an optional extra.

At the end, the subjects were asked to rate whether they preferred to use a) the IASS b) the MS or c) no seating system during the study. For this purpose, they were asked to rank the three choices.

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[5] In the brackets the name of the respective seating system was given depending on the condition.

7.2.2.2 Driving parameters

In order to evaluate the driving performance in the simulator, three parameters were captured that give information about the lane tracking ability. As described in Chapter 2.4.2 all measures increase with increasing passive driver fatigue. The parameters were calculated from the raw signals in Mathworks® Matlab® R2018b.

Standard deviation of lane position (SDLP)

SDLP describes the calculation of the standard deviation of the vehicle's lane position. The center of the middle lane was chosen as the zero point (the subject's task was to drive in this lane). The SDLP was now calculated from the standard deviation of the lateral deviation from this zero point.

Mean departure from lane (MDFL)

MDFL was calculated as the mean deviation of the vehicle from the middle lane. As long as the vehicle was driving within the lane, MDFL was 0. If the vehicle left the middle lane, the difference between the outer edge of the vehicle and the outer edge of the middle lane was calculated. The further and longer the vehicle was outside the middle lane, the greater MDFL became. As the lane must have already been left before MDFL increases, it is a measure of an advanced stage of fatigue.

Standard deviation of steering angle (SDSA)

This parameter calculates the standard deviation of the steering angle.

7.2.2.3 Vital parameters

Three vital parameters were captured: *heart rate (HR)*, *heart rate variability (HRV)* und *skin conductance level (SCL)*. More detailed information about these parameters can be found in Chapter 2.4.4. In this study, the listed parameters are expected to be influenced by the level of passive driver fatigue, physical activity and task complexity. As described in Chapter 2.4.4 elevated passive driver fatigue leads to a decreased heart rate and skin conductance level and increased heart rate variability. Physical activity (Boettger et al., 2010; Hottenrott, 2002; Nikolic-Popovic & Goubran, 2011; Such & Meyer, 2010) and increased task complexitiy (Coughlin et al., 2011; Mehler et al., 2009, 2011; Paxion et al., 2014; Reimer

& Mehler, 2011) are expected to have the opposite effects: increased heart rate and skin conductance as well as a reduction of heart rate variability. The parameters were calculated from the raw signals in Mathworks® Matlab® R2018b.

Heart rate and Heart rate variability

The ECG signal was first subjected to analog bandpass filtering with cutoff frequencies of 0.9 Hz and 100 Hz. The filter was integrated in the biofeedback device as standard. No further digital filtering was applied as the signal was sufficiently good. Afterwards, the heart rate was extracted from the signal with the PhysioNet-Cardiovascular-Signal-Toolbox (Goldberger et al., 2000; Vest et al., 2018). The jqrs method was chosen as a beat detector because the IASS can be classified as low intensity physical activity. The RR-peak detection for the calculation of the heart rate was visually inspected after the processing steps and showed excellent reliability. From the RR intervals (RRI), heart rate was calculated with equation 11. Heart rate variability was calculated with the RMSSD method according to Camm et al. (1996) with equation 12.

$$Heart\ rate\ (BPM) = \frac{1\ min}{\left(\frac{RRI_1 + \cdots + RRI_n}{n}\right)} \tag{11}$$

$$HRV\ (RMSSD) = \sqrt{\frac{\sum_{i=1}^{n}(RRI_{i+1} - RRI_i)^2}{n_{RR_i}}} \tag{12}$$

Skin conductance level

Since SCL data shows a high intersubject variability, normalization should be applied before making statistical inferences. For this, Collet et al. (2005) suggest dividing the data by the mean value of a separate reference measurement over two minutes. The reference measurement should be taken at rest while sitting in the seat. As no separate reference measurement was captured in this study, the mean value of the first 2 minutes of each data set was used as a reference.

7.2.2.4 Eye tracking parameters

The eye tracking was captured to provide information on both passive driver fatigue and task complexity. The parameters were calculated from the raw signals in Mathworks® Matlab® R2018b.

Passive driver fatigue

As described in Chapter 2.4.3, different eye tracking parameters can be used to evaluate passive driver fatigue. From those, *eyelid distance (ED)*, *blink frequency* (BF) and *blink duration (BD)* were used in this study. Eyelid distance is expected to increase with elevated PDF, whereas the last two decrease.

Task complexity

Literature shows, that increased task complexity through additional mental tasks while driving increases the *pupil diameter* (Palinko et al., 2010; Recarte & Nunes, 2000; Y. Wang et al., 2010). As the IASS is a motor secondary task, the pupil diameter is expected to increase when using the system.

7.2.3 Experimental Design

7.2.3.1 Driving task

The driving task was to keep the vehicle in the middle lane with a speed limiter set at 60 km/h. On the right lane, vehicles were travelling at 42 km/h, and on the left side, vehicles passed by with 82 km/h. The vehicle was driven with automatic transmission. No additional assistance systems were activated.

7.2.3.2 Conditions

The study included three conditions. The first condition was the *active condition* (AC), in which the IASS was used. In the *passive condition* (PC), the massage seating system on which the IASS is based was used (see Chapter 4 and 6). That said when the air bladders opened in the PC, the subjects were instructed not to actively push against them but to allow themselves to be passively mobilized. In Chapter 2.5.2, different countermeasures against PDF were listed. The MS represents an additional stimulus and can be assigned to cluster a), whereas the IASS represents an additional motor task and can be assigned to cluster c). No intervention was included in the *control condition* (CC). Before the start of the programs in the active and passive condition, there was a short introduction to explain each intervention. In the AC, the introduction explained the movement task. In the PC, the subjects were instructed not to interact with the system.

7.2.3.3 Procedure

Each testing day consisted of two sessions, one in the morning (08:15 am - 12:30 pm) and one in the afternoon (01:30 pm - 5:45 pm). The IASS aims at reducing monotony and thus passive driver fatigue. The goal is not to reduce sleepiness. Therefore, no sleep deprivation was imposed and the study took place during the day (Bier et al., 2018). To keep the lighting conditions constant during the experiment, the shutters were closed and the lights switched on. Each subject completed one of the two sessions. During each session, the three conditions were completed in succession (repeated measures design). The order of conditions was randomized, such that all possible combinations were equally represented in the morning and afternoon sessions, as weariness is influenced by time on day (Lenné et al., 1997). Figure 22 illustrates the procedure of the study. In the beginning, the subjects completed the preliminary questionnaire. Afterwards the subjects sat into the simulator and adjusted the seat individually until they felt comfortable similar to other studies (e.g. Falou et al., 2003). The next step was the calibration procedure of the IASS, which is analogous to the passive condition. This was followed by a training session of the IASS (without driving). During the training, the user interface from Figure 18 was shown. Afterwards, the subjects completed a five-minute training session in the driving simulator. According to Sahami & Sayed (2013) a training session with solely holding a straight line is not sufficient to develop driving skills, therefore the subjects were asked to drive slalom and perform emergency braking. Subjects were allowed to end the training session earlier if they felt comfortable with driving, which is in line previous studies (Fisher et al., 2007).

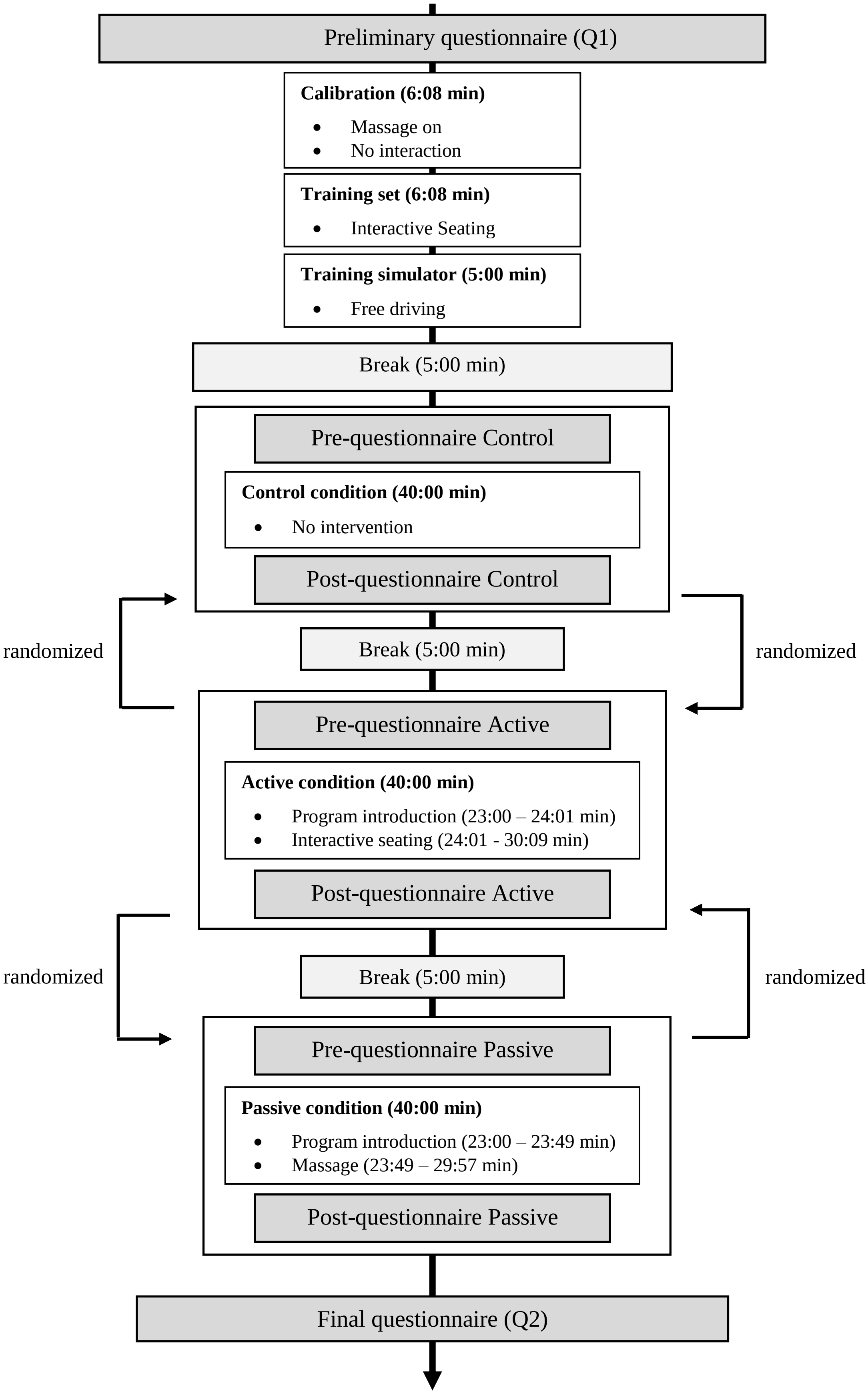

Figure 22: *Scheme of the study procedure. The duration of each session was around 4:15 hours. However, the exact duration varied depending on how long the subjects needed to answer the questionnaires.*

After these preparatory steps and a five-minute break, the three conditions were completed in randomized order. Regarding the duration of the conditions, it was important to keep them as short as possible, but long enough to induce fatigue. According to Bier et al. (2018), 40 minutes is the best duration to meet both requirements. In the control condition, subjects used the simulator for 40 minutes without any intervention. In the AC and the PC, the introduction started after 23 minutes, followed by the respective intervention. After the intervention, subjects continued driving, until the total duration of the ride was 40 minutes. It should be emphasized that the user interface (Figure 18) was not visible in the AC. In contrast to the training session, the movement instructions were only presented in auditory (audio track) and tactile (air bladders) form. The movement feedback was given visually (LEDs) and tactilely (vibrating elements). A 5-minute break was included between conditions, in which subjects were asked to stand up and drink to refresh themselves. A pre-questionnaire was completed before each condition and a post-questionnaire afterwards. After finishing all three conditions, the subjects completed a final questionnaire.

For the evaluation of the simulator-, vital- and eye tracking data, three time intervals (TIs) were define that are listed in Table 3. Due to the different lengths of the introductions, the intervention in the AC started slightly later as in the PC. The start of the time interval *Int.* in the control condition was defined as the mean between the active and passive condition.

Table 3: *Begin and duration of the time intervals in the conditions.*

	Time interval		
	Prae (9:50 min)	*Int.* (6:08 min)	*Post* (9:50 min)
Active condition	13:10 – 23:00 min	24:01 – 30:09 min	30:09 – 39:59 min
Passive condition	13:10 – 23:00 min	23:49 – 29:57 min	29:57 – 39:47 min
Control condition	13:10 – 23:00 min	23:55 – 30:03 min	30:03 – 39:53 min

7.2.4 Subjects

The subjects were employees of Mercedes-Benz AG, but they were not familiar with the project or the objectives of the study. Thirty-eight subjects without any need for vision correction participated in the study. Three datasets had to be excluded from the analysis. The dataset of the first subject had to be excluded, due to technical problems with the shutters on the windows. For this reason, it was not possible to maintain the standardization of the lightning. Another subject suffered from motion sickness. The third subject went off the road during the control condition, which stopped the simulation. As a result, fourteen female and twenty-one male valid subjects (N = 35) were included in the analysis. The mean age was 32.1 years (± 9.3 years, range from 19 to 61 years), mean body mass 74.7 kg (± 12.0 kg, range from 53.8 to 106.8 kg), and mean height 171.8 centimeters (± 7.9 centimeters, range from 157.0 to 186.0 centimeters). Before participating in the study, each subject gave written informed consent.

7.2.5 Statistical analysis

The statistical analysis was performed in IBM® SPSS® Statistics 24. With the exception of effect sizes, these were calculated in Microsoft® Excel® 2013.

7.2.5.1 Questionnaires

Comfort, discomfort, passive driver fatigue and workload were visualized with box plots. Afterwards, these questionnaires were analyzed with Friedman tests, the effect-size is indicated with Kendall's W as proposed by Tomczak & Tomczak (2014). A detailed classification of the effect size is not provided, but Tomczak & Tomczak (2014) report a range from 0 (no effect) to 1 (perfect effect). Subsequently, Dunn-Bonferroni post hoc tests were conducted with multiple comparison adjustment, effect size was calculated with correlation coefficient r (Tomczak & Tomczak, 2014). J. Cohen (1992) provides the following classification: small ($0.1 \leq r < 0.3$), medium ($0.3 \leq r < 0.5$) and large effect ($0.5 \leq r$).

The Likert-scales for the assessment of user experience were only queried after the active and passive condition which means that only two samples were compared. Accordingly, the analysis for this part of the questionnaires was done with Wilcoxon signed-rank tests. Because the questionnaire included seven questions, p-values were Bonferroni corrected. The effect size is indicated with correlation coefficient r (Tomczak & Tomczak, 2014).

7.2.5.2 Simulator-, vital- and eye tracking data

The simulator-, vital- and eye tracking data were analyzed using MANOVAs and ANOVAs. Not all data was normally distributed. However, since MANOVA and ANOVA are considered to be robust against a violation of normal distribution if sample sizes are equal, they were considered suitable for this study (Field et al., 2012; Schmider et al., 2010; Wilcox, 2012). Nevertheless, the result of the Shapiro-Wilk test for each dataset is listed in Appendix C. If the assumption of sphericity had been violated, degrees of freedom for the ANOVAs were corrected using Greenhouse-Geisser. Pairwise comparisons were conducted using paired t-tests with Bonferroni correction for multiple testing. Effect size was calculated with Cohen's D according to Tomczak & Tomczak (2014). J. Cohen (1992) provides the following classification: small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large effect ($0.8 \leq d$).

7.3 Results

7.3.1 Questionnaires

7.3.1.1 Passive driver fatigue

Two subjects did not complete all questionnaires. Therefore, 33 datasets were included in the analysis. Changes over time were calculated by subtracting the ratings after the conditions from those before. Positive values indicate an increase of passive driver fatigue and vice versa. As shown in Table 4 and Figure 23, the lowest levels for PDF occurred by far in the AC, followed by the PC and the CC. Additionally, the lower quartiles in Figure 23 reflect that PDF remained constant or even decreased over time in the AC for one fourth of the subjects.

Table 4: *Development of passive driver fatigue in the conditions.*

Condition	Mean	Standard deviation (SD)	Median	Min	Max
AC	0.5	1.7	1.0	-3.0	5.0
PC	2.4	1.4	2.0	0	7.0
CC	2.8	1.8	3.0	0	7.0

The Friedman test revealed significant differences between conditions: $\chi2(2) = 21.68$, $p < 0.001$, $W = .33$. Dunn-Bonferroni post hoc tests revealed that PDF increased significantly less in the AC compared to the CC ($z = 0.98$, $p < .001$, $r = .17$) as well as in the PC ($z = 0.83$, $p = .002$, $r = .15$). A small effect size was found for both comparisons. No significant differences were found between the PC and the CC.

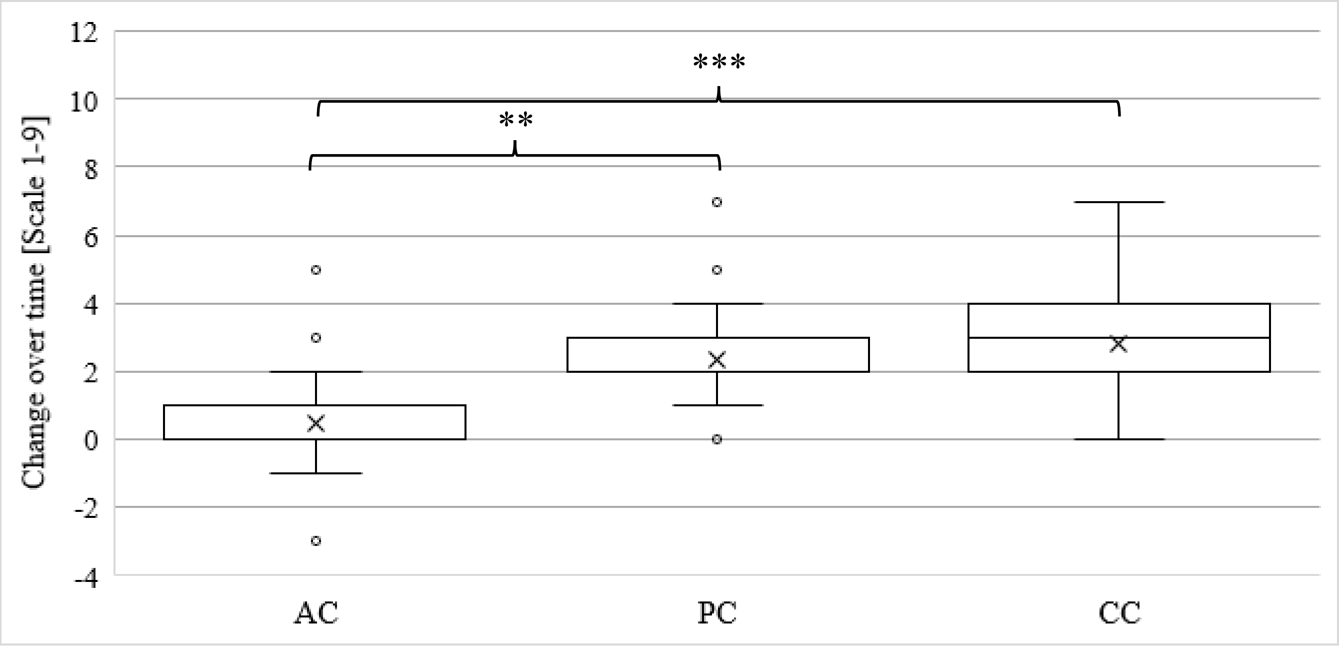

Figure 23: *Boxplot for the illustration of the change in fatigue in each condition. The lower and upper end of the box mark the first and the third quartile. Inside the box, the median is at the level of the horizontal line, and the mean is at the cross. The whiskers show the minima and maxima. Outliers are defined as values outside the one and a half interquartile range. Statistically significant differences are highlighted with: ** p < .01; *** p < .001.*

7.3.1.2 Sitting comfort

The questionnaires on seating comfort were fully completed by all 35 subjects. The participants rated comfort in the pre- and post-questionnaire of each condition. Changes over time were calculated by subtracting the ratings after the condition from those before. After that, overall comfort was calculated by averaging all five comfort statements. Negative values represent a decrease of comfort over time and vice versa. As shown in Table 5 and Figure 24, comfort only slightly decreased over time in all three conditions. The greatest loss of comfort occurred in the CC followed by the PC and the AC.

The Friedman test revealed significant differences between conditions, however with a small effect size: $\chi2(2) = 11.01$, $p = 0.004$, $W = .16$. Dunn-Bonferroni post hoc tests showed that the loss of comfort was significantly lower in the AC compared to the CC, again with a small effect size ($z = -0.77$, $p = .004$, $r = .13$). There were no significant differences between the other conditions.

Table 5: *Development of comfort in the conditions.*

Condition	Mean	SD	Median	Min	Max
AC	-0.2	0.8	-0.2	-2.0	2.6
PC	-0.8	0.9	-0.8	-3.2	0.8
CC	-1.2	0.9	-1.0	-3.6	0.4

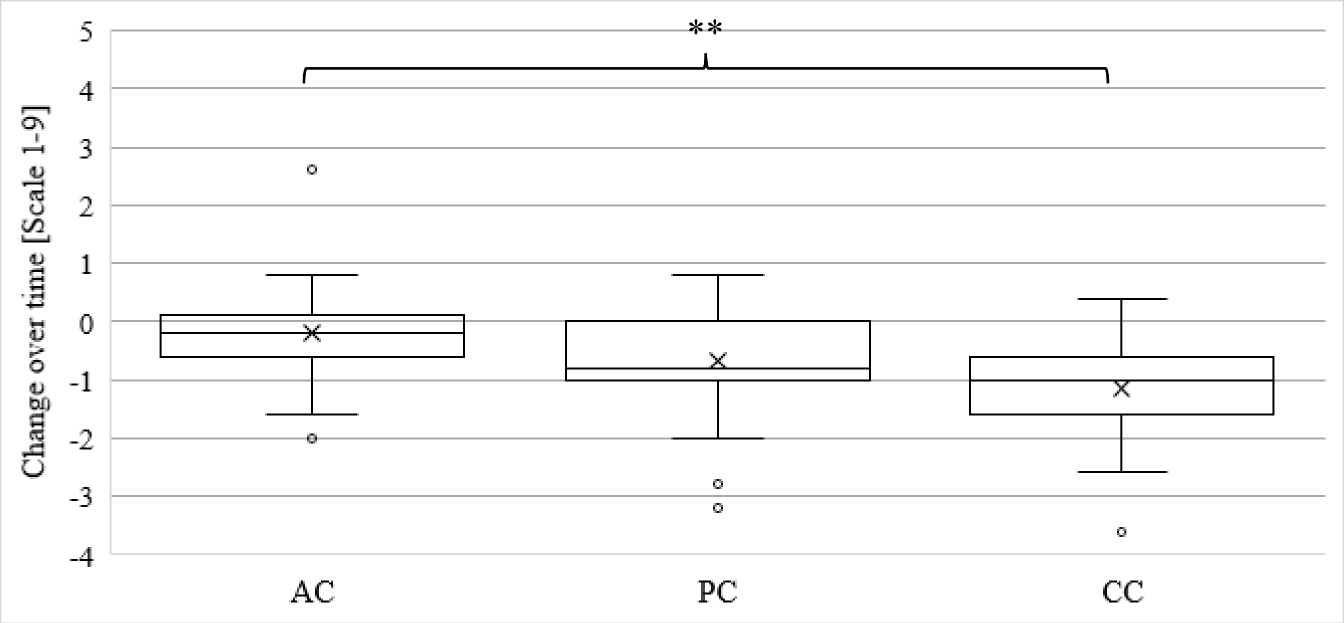

Figure 24: *Boxplot for the illustration of the change in sitting comfort in each condition. The layout of the boxplot is identical to Figure 23. Statistically significant differences are highlighted with: ** p < .01.*

7.3.1.3 Sitting discomfort

All 35 subjects completed all discomfort questionnaires. The discomfort questionnaire was equally analyzed as the comfort questionnaire. As shown in Table 6 and Figure 25, similar to comfort, discomfort only slightly changed over time in all three conditions. The smallest increase occurred in the AC, followed by the PC and the CC.

Table 6: *Development of discomfort in the conditions.*

Condition	Mean	SD	Median	Min	Max
AC	0.2	0.8	0.2	-1.7	2.2
PC	1.0	0.8	0.8	-0.2	2.3
CC	1.3	1.3	1.2	-1.8	5.0

The Friedman test revealed significant differences between conditions: $\chi 2(2) = 22.07$, $p < .001$, W = .32. Dunn-Bonferroni post hoc tests revealed that discomfort increased significantly less in the AC compared to the CC, but with a small effect size ($z = 1.00$, $p < .001$, $r = .17$). Discomfort also increased less in the AC compared to the PC, also with a small effect size ($z = 0.89$, $p = .001$, $r = .15$). No significant difference was found between the PC and the CC.

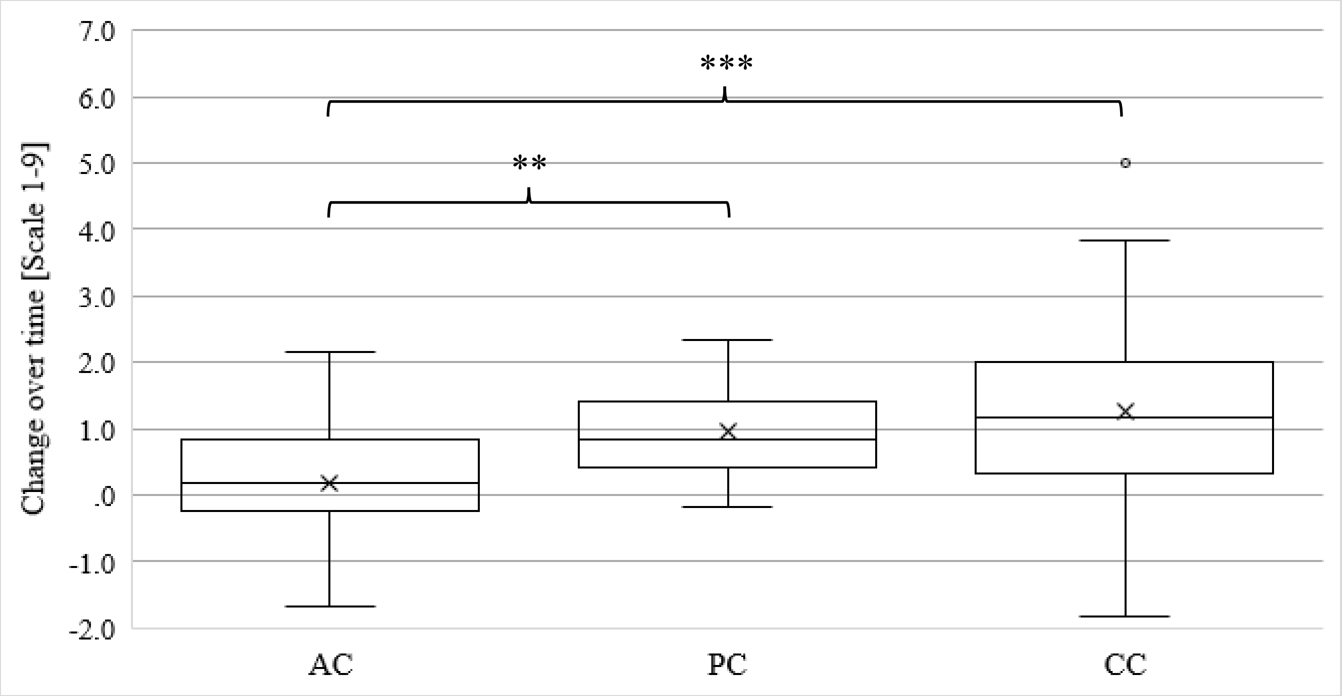

Figure 25: *Boxplot for the illustration of the change in sitting discomfort in each condition. The layout of the boxplot is identical to Figure 23. Statistically significant differences are highlighted with: ** p < .01; *** p < .001.*

7.3.1.4 Emotional perception

Two subjects did not complete the entire questionnaire, resulting in 33 datasets that were included in the analysis. In the preliminary (Q1) and final questionnaire (Q2), it was asked which emotion a perfekt car seat should elicit. In the post-questionnaire after each condition, the subjects had to state which emotion the respective seat elicited. Figure 26 shows the emotions ordered from unpleasant to pleasant.

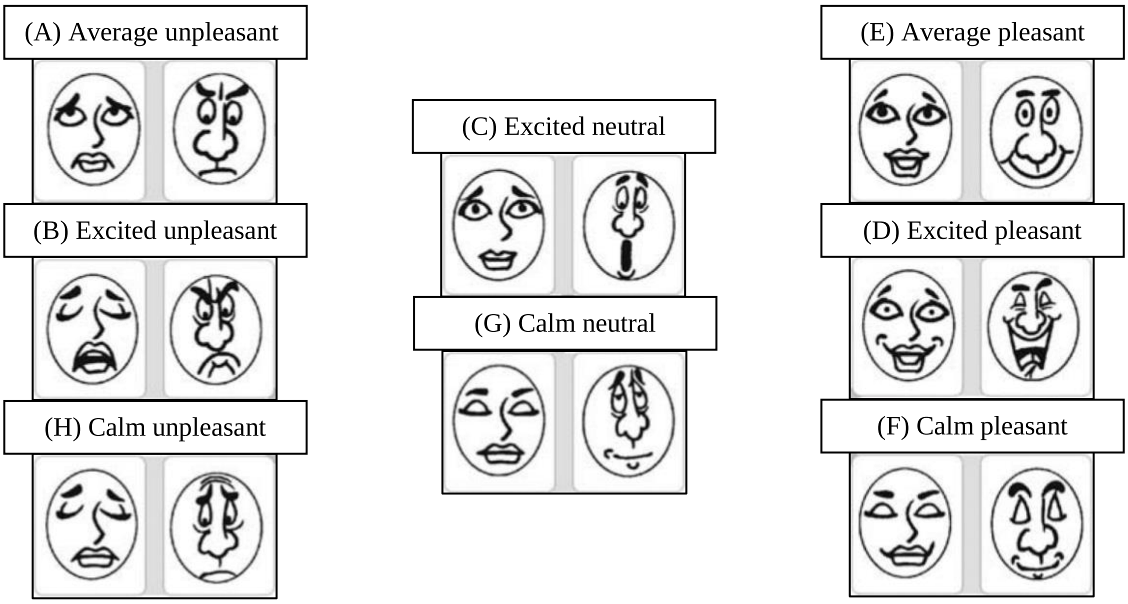

Figure 26: *Emotions ordered from unpleasant (left) to pleasant (right). Adopted from Desmet et al. (2001).*

Emotional expectation of a seat

According to Figure 27, the pleasant emotions (E, F, and D) make up 91 % in the preliminary questionnaire. Emotion E was rated by 67 % of the subjects, followed by F and D. The remaining participants chose emotion G. In the final questionnaire (Q2), the proportion of pleasant emotions increased up to 97 %. Again, Emotion E was most frequently mentioned, but decreased of 12 to 55 %. Emotion D received the largest increase and grew to a share of 21 %. The frequency of emotion G dropped to 3 %.

Emotional perception of the seat in the conditions

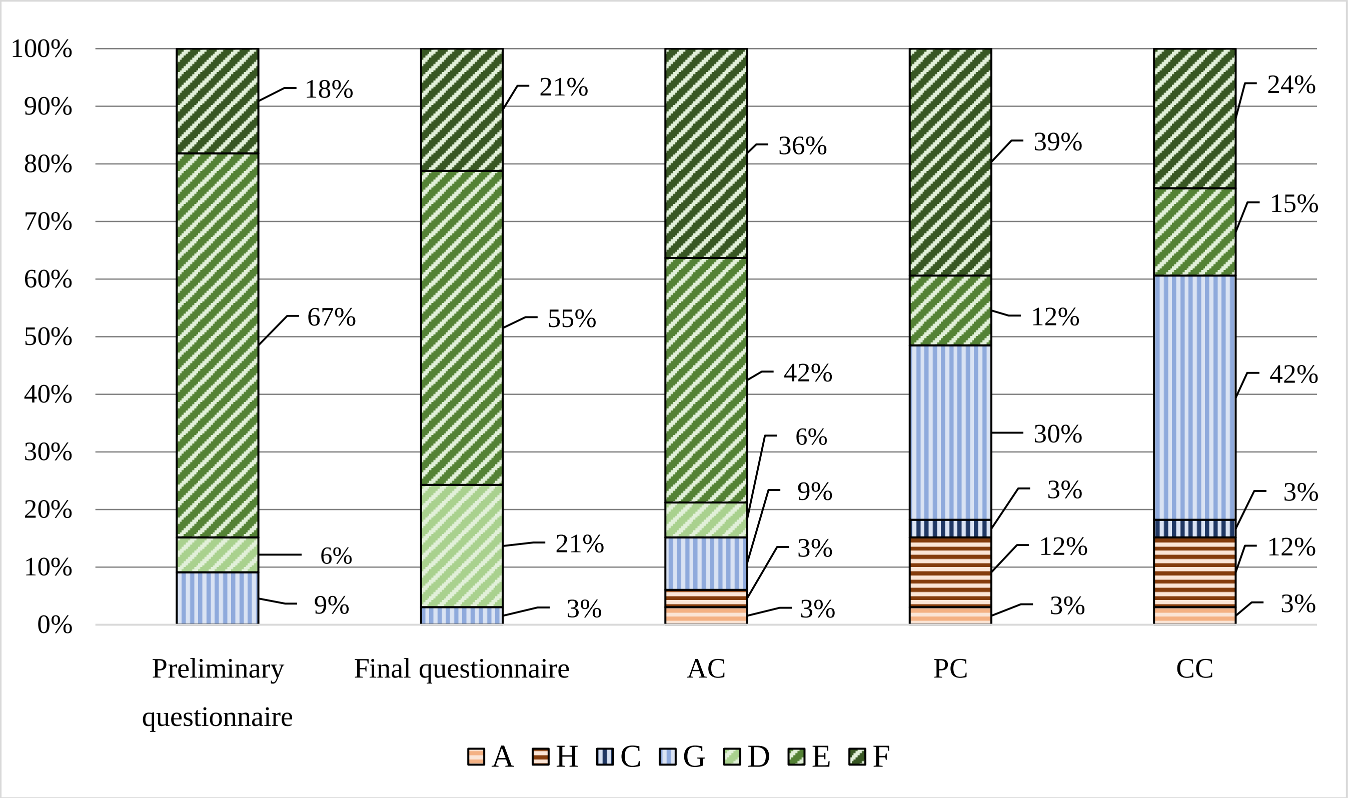

Figure 27: *Response distribution of the emotional evaluation in the different questionnaires.*

This subsection compares the emotional perceptions of the seat in the different conditions. First, it is evident from Figure 27 that the negative emotions (A, B and H) were chosen less frequently in the AC with 6 % compared to the PC and the CC with 15 % each. Likewise, the neutral emotions (C and G) appeared less common in the AC with 9 % in comparison to the PC with 33 % and the CC with 45 %. Complementing these findings, pleasant emotions were most frequently experienced in the AC at 84 %. In particular, Emotion E, which was stated most often as the desired emotion in the previous section, is much more common with 42 % compared to the PC with 12 % and the CC with 15 %. The emotion 'excited pleasant' was only perceived in the AC. The emotion 'calm pleasant' was almost equally represented in the AC with 36 % and in the PC with 39 %.

Expectation fulfillment of the seat in the conditions

The final step was to analyze the degree to which the seat matched the subject's expectations in the three conditions. For this purpose, it was calculated, for how many subjects the emotional expectation from the final questionnaire (Q2) was similar to the evaluation of the seat in each condition. As can be seen in Table 7, the seat with the IASS fulfilled the expectations of about half the subjects. For the seat with no seating system and the MS, this was only the case for approximately one fifth of the subjects.

Table 7: *Share of subjects in which the seats fulfilled the emotional expectation.*

	Fulfillment of emotional expectation
Interactive seating system	48 %
No seating system	21 %
Massage seating system	18 %

7.3.1.5 Workload

The DALI questionnaire was handed out after each condition. For the analysis, the questions were assigned to three clusters. The first cluster includes questions 1 - 5 that represent the overall task difficulty (cognition, sensory demands and time constraints). The second cluster represents the interference of the task, queried with question 6. The third part, question 7, represents situational stress.

The division into these three categories helps to give a better understanding if the effects of the seating systems are in line with the proposed model from Chapter 2.2.3.3. The model depicts task complexity in relation to monotony and workload. In this context, it is important to consider, that task complexity is the objective property of the task and task difficulty is the amount of an individual's resources required for task performance (see Chapter 2.2.3.1). If subject's now rate their subjective experience of the task, they describe task difficulty and not task complexity. However, both constructs are closely related. Therefore, it is assumed that also task difficulty can help to give first insights into the validity of the model.

According to the model, a successful measure against passive driver fatigue should reduce monotony-related fatigue (represented by situational stress) while keeping the increase in overall task complexity/difficulty and interference low.

Overall task difficulty

Two subjects did not complete the entire questionnaire. Therefore, 33 datasets were included in the analysis. As shown in Table 8 and Figure 28 the level of overall task difficulty was generally low in all conditions. Task difficulty was the highest in the AC, followed by the PC and the CC.

Table 8: *Ratings of overall task difficulty in the conditions.*

Condition	Mean	SD	Median	Min	Max
AC	3.6	2.8	3.0	0.4	11.0
PC	2.4	2.2	1.8	0.0	8.4
CC	1.8	1.6	1.6	0.0	6.6

The Friedman test revealed significant differences between conditions, however with a small effect size: $\chi2(2) = 15.25$, $p < .001$, $W = .23$. Dunn-Bonferroni post hoc tests showed that overall task difficulty was significantly higher in the AC compared to the CC, with a small effect size ($z = 0.94$, $p < .001$, $r = .16$). No significant difference was found for any other comparison.

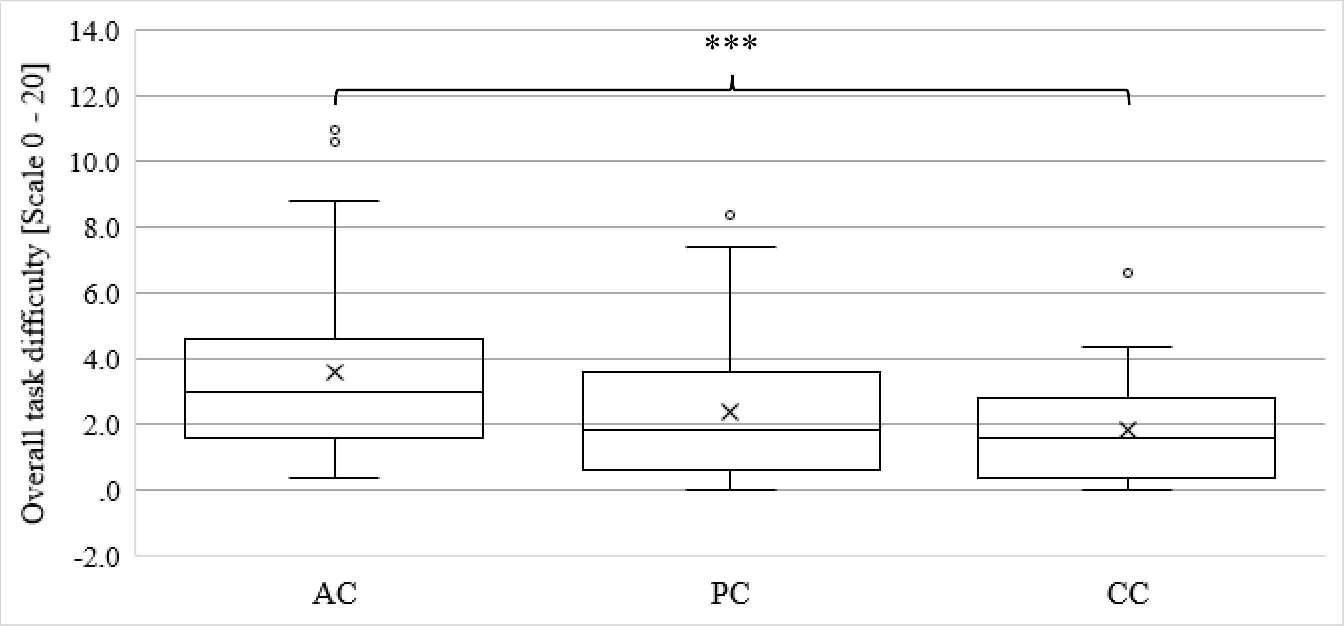

Figure 28: *Boxplot showing the distribution of overall task difficulty in the conditions. Statistically significant differences are highlighted with: *** p < .001.*

Interference

Since one subject did not complete the entire questionnaire, 34 datasets were included in the analysis. As shown in Table 9 and Figure 29, almost no interference occurred in the CC. Through the use of the MS, the interference in the PC marginally increased. The interquartile range was equal in the PC and the CC; therefore, outliers seem to have mostly caused the mean difference. Through the use of the IASS in the AC, the subjects experienced a low to moderate level of interference.

Table 9: *Ratings of interference in the conditions.*

Condition	Mean	SD	Median	Min	Max
AC	4.2	3.2	3.0	0.0	13.0
PC	1.4	1.8	1.0	0.0	8.0
CC	0.5	1.0	0.0	0.0	4.0

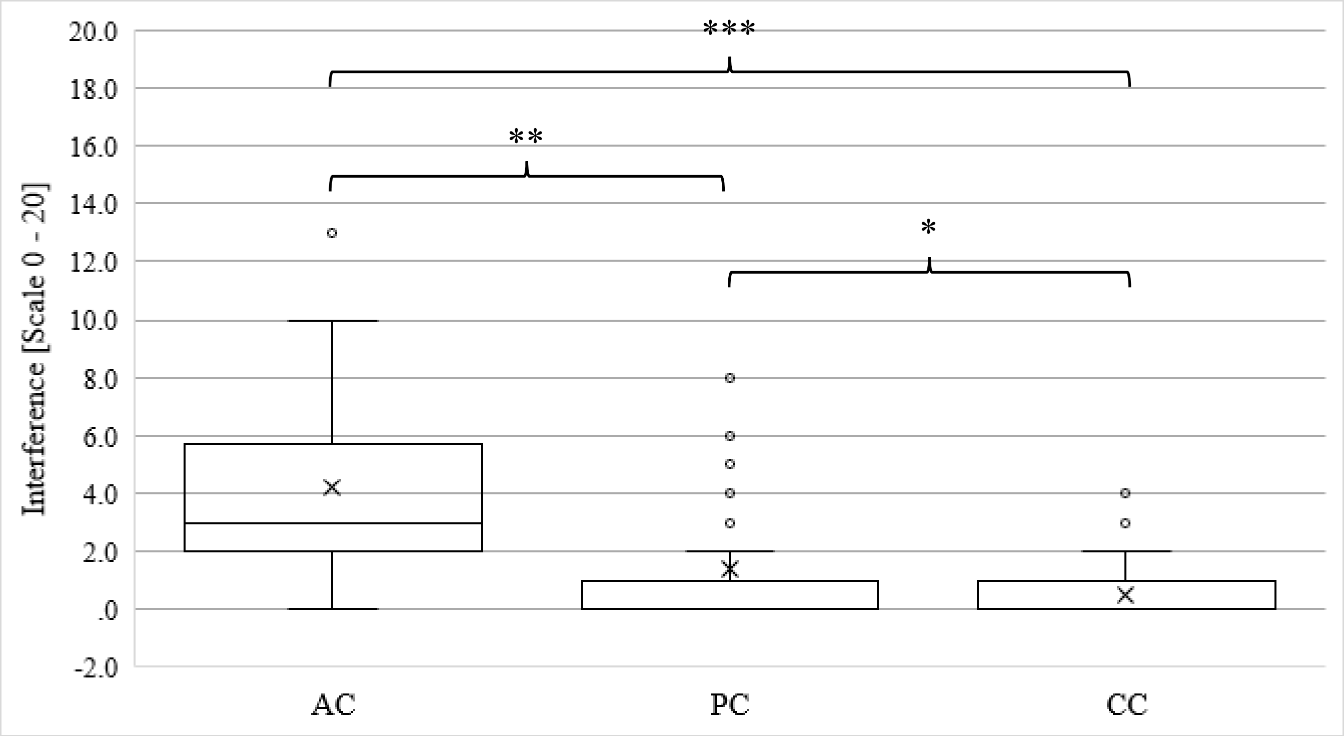

Figure 29: *Boxplot showing the distribution of interference in the conditions. Statistically significant differences are highlighted with: * p < .05; ** p < .01; *** p < .001.*

The Friedman test revealed significant differences between conditions with a medium effect size: $\chi2(2) = 39.01$, $p < .001$, $W = .59$. Dunn-Bonferroni post hoc tests revealed that interference was significantly higher in the AC compared to the CC, with a small effect size ($z = 1.40$, $p < .001$, $r = .24$).

Interference was higher in the AC compared to the PC as well, also with a small effect size ($z = 0.77$, $p = .005$, $r = .13$). In addition, significantly higher interference was found in the PC compared to the CC, also with a small effect size ($z = 0.63$, $p = .027$, $r = .11$).

Situational stress

Since one subject did not complete the entire questionnaire, 34 datasets were included in the analysis. Following Table 10 and Figure 30 the lowest situational stress occurred in the AC, followed by the CC and the PC. However, Friedman test revealed no significant difference between any conditions with $\chi2(2) = 4.91$, $p < .086$.

Table 10: *Ratings of situational stress in the conditions.*

Condition	Mean	SD	Median	Min	Max
AC	5.4	4.3	4.0	0.0	18.0
PC	8.2	5.7	7.5	0.0	20.0
CC	7.4	5.2	7.0	0.0	18.0

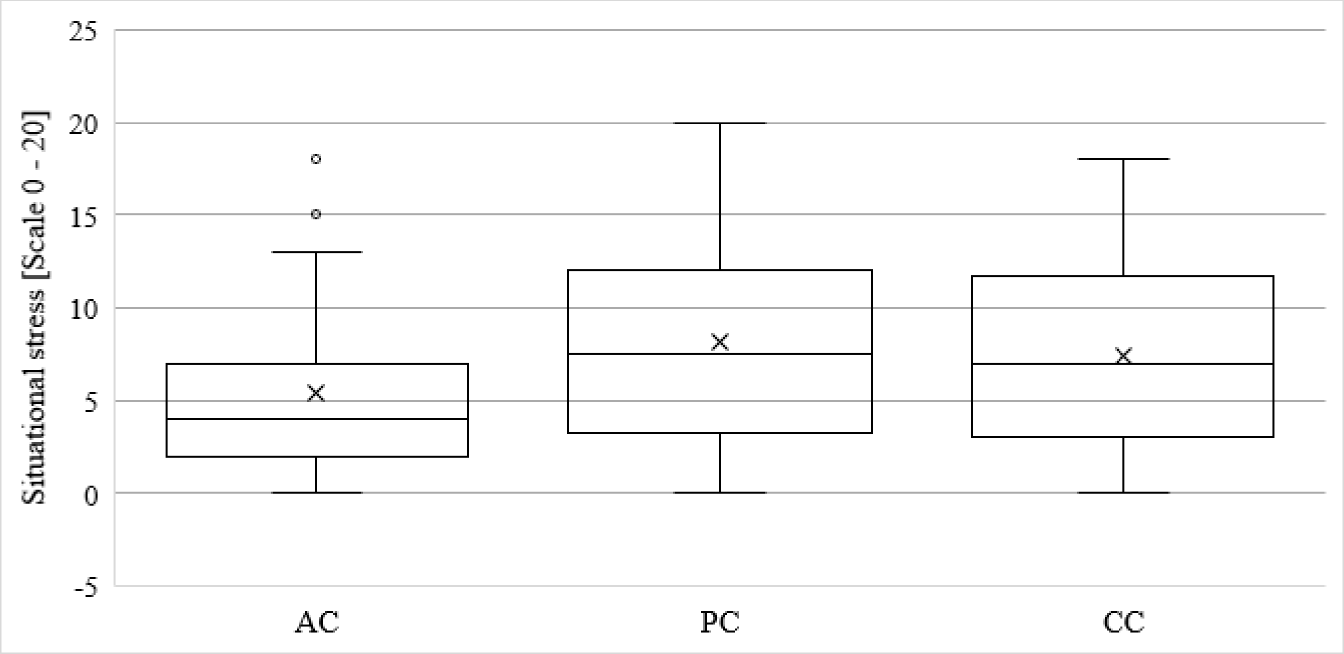

Figure 30: *Boxplot showing the distribution of situational stress in the conditions.*

7.3.1.6 User experience

Two subjects did not complete the whole questionnaire. Therefore, 33 datasets were included in the analysis. The assessment of user experience consisted of two parts. After the AC and the PC the seating systems had to be rated on seven Likert scales. In the final questionnaire (Q2), the subjects directly compared both systems.

Likert scales

As shown in Table 11 the IASS promoted significantly more wellbeing, activation and fun in comparison to the MS. The IASS was also significantly more exhausting; however, the rating of 2.2 indicates a rather low absolute level of strain. Additionally, the IASS was rated to be significantly more useful. A similar degree of relaxation was induced by both systems with a p-value of 1.0. The subjects were more excited by the IASS regarding the mean differences; however, this comparison just missed significance with a p-value of .58.

Table 11: *Rating of user experience for the interactive seating system (IASS) and massage seating system (MS). Items that differed significantly (p < .05) between both systems are highlighted with *.*

Question	Seat. system	Mean ± SD	Min	Max	Median	z	p	| r |
Well-being*	IASS	4.6 ± 1.0	2	6	5	-3.32	.006	0.56
	MS	3.7 ± 1.1	2	6	4			
Activation*	IASS	4.6 ± 1.2	2	6	5	-4.42	<.001	0.75
	MS	2.8 ± 1.3	1	6	3			
Fun*	IASS	4.7 ± 0.9	3	6	5	-3.67	.002	0.62
	MS	3.7 ± 1.2	1	5	4			
Exhaustion*	IASS	2.2 ± 1.1	1	5	2	-4.02	<.001	0.68
	MS	1.3 ± 0.6	1	3	1			
Usefulness*	IASS	4.9 ± 0.9	3	6	5	-3.44	.004	0.58
	MS	4.1 ± 1.1	1	6	4			
Relaxation	IASS	3.7 ± 0.9	2	6	4	-0.51	1.0	0.09
	MS	3.6 ± 1.2	2	6	4			
Excitement	IASS	4.4 ± 1.0	2	6	5	-2.64	.058	0.45
	MS	3.7 ± 1.1	1	6	4			

Comparison of both seating systems

As shown in Table 12 the predicted frequency of use for both seating systems was generally high, with marginally better ratings for the IASS. However, Table 13 shows, that substantially more participants stated they would order the IASS as an optional feature compared to the MS. In the last question (which was validly answered by only 32 participants), subjects ranked the seating systems depending on which they preferred to use in this study. Table 14 demonstrates that the majority of the subjects rated the IASS on the first place, followed by the MS. Not using any system at all was consistently ranked last, with exception of one respondent which equals 3% of the subjects.

Table 12: Predicted user frequency of both seating systems.

Would you use the seating system frequently? (N = 35)	Frequency of answers	
	IASS	MS
I fully agree	46 %	40 %
I rather agree	43 %	49 %
I rather disagree	9 %	9 %
I do not agree at all	3 %	3 %

Table 13: Predicted consumer acceptance of both seating systems.

Would you order the seating system as an optional feature? (N = 35)	Frequency of answers	
	IASS	MS
I fully agree	31 %	3 %
I rather agree	40 %	57 %
I rather disagree	26 %	34 %
I do not agree at all	3 %	6 %

Table 14: Preference order of the seating systems.

What was your favorite seating system to use during the study? (N = 32)	Frequency of answers		
	IASS	MS	No Sys.
First Place	72 %	28 %	0 %
Second Place	25 %	72 %	3 %
Third place	3 %	0 %	97 %

7.3.2 Driving parameters

For the statistical analysis of the driving simulator data, a 3 x 3 two-way repeated-measures MANOVA was carried out. The dependent variables were the simulator parameters SDLP, MDFL and SDSA. The two independent variables were time interval (Prae/Int./Post) and condition (AC/PC/CC). All datasets (N = 35) were included in the analysis. As can be seen in Table 15, the MANOVA revealed a significant main effect for time interval and condition. In addition, a significant interaction effect was found. Therefore, a univariate 3 x 3 two-way repeated measures ANOVA was then calculated for each of the dependent variables. The two independent variables were time interval (Prae/Int./Post) and conditions (AC/PC/CC). In the section of each parameter the results of the ANOVAs are reported in short, detailed values are listed in Appendix D. Additionally, in the section of each parameter a figure is included, which illustrates the mean values and variances in the different conditions and time intervals. A table with exact values can be found in Appendix E.

Table 15: *Results of the MANOVA for the analysis of the driving simulator data.*

	Pilla's trace	F	Df_1	Df_{error}	Sig.	Partial η^2
TI	.48	4.40	6	29	p = .003	.48
Condition	.44	3.79	6	29	p = .007	.44
TI * cond.	.67	3.90	12	23	p = .002	.67

7.3.2.1 Standard deviation of lateral position

Figure 31 illustrates the mean SDLP of all subjects over time. The illustration shows, that the SDLP generally increased over time in all conditions. No differences between conditions are visible until the introduction (at 23:00 min). During the introduction, SDLP decreased in both the AC and the PC. Afterwards, SDLP increased again in the PC (from 23:49 min), whereas it kept decreasing in the AC (from 24:01 min). In the AC, SDLP remained at a lowered level until the end of the IASS. Afterwards, in time interval *Post*, SDLP slowly returned to the level of the CC; until 34:00 min, the SDLP was at the same level again. With the beginning of *Int.* until the end of *Post* in the PC, SDLP was consistently higher compared to the CC, although the difference was rather small.

These observations are reflected in the statistical analysis (see Table 16 and Figure 32). The ANOVA revealed a significant main effect for time interval and condition as well as a significant interaction effect.

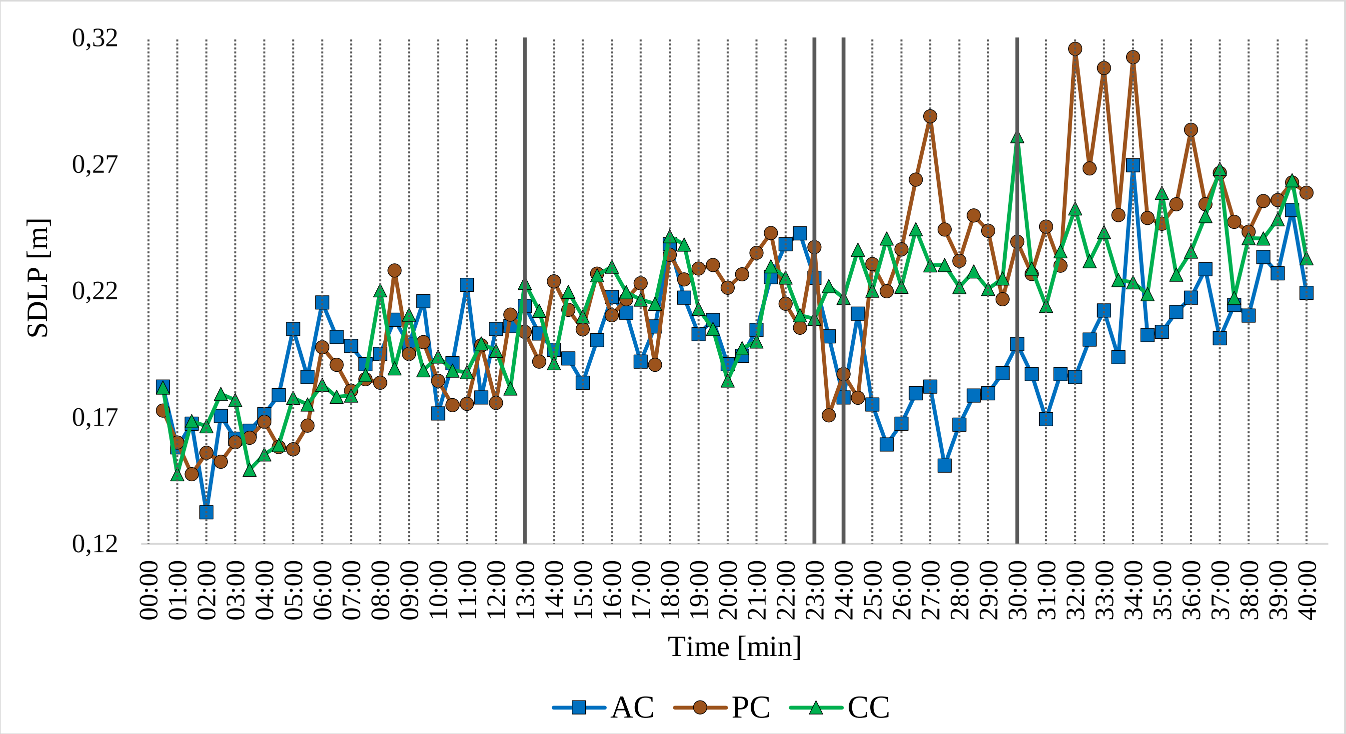

Figure 31: *Development of SDLP in the conditions. The mean curve for all subjects was calculated. The curve was then divided into 30-second segments and the mean was calculated for each of those segments. Afterwards the mean was plotted on the time axis at the end of the related time interval. For example, the first markers at 00:30 min indicates the average SDLP of all subjects from 00:00 – 00:30 min. The first vertical line represents roughly the start of time interval Prae, the third of Int. and the fourth of Post. The second vertical line indactes the beginning of the introduction.*

In *Prae*, no significant difference was found between conditions. During time interval *Int.*, SDLP was significantly lower in the AC compared to both the CC and the PC. No significant difference was found between the CC and the PC. In time interval *Post*, SDLP was significantly lower in the AC compared to the CC. Even though SDLP was the highest in the PC, nor the comparison with the AC neither with the PC revealed significant differences.

Within conditions, SDLP significantly increased over time from *Prae* to *Post* in the CC. Even though the same pattern occurred regarding the mean values in the PC, the comparison between *Prae* and *Post* just missed significance with p = .057. In the AC, SDLP did not significantly increase over time. Instead, significantly lower values were found in *Int.* compared to *Prae* and *Post*. Effect sizes for the post hoc comparisons ranged between small and medium.

Table 16: *Post hoc comparisons for SDLP. Comparisons are listed with p < .06 and additionally marked with * if they were significant (p < .05).*

Compare	Mean difference	95% CI		Sig. (| *d* |)
		Lower	Upper	
AC *Prae* vs. AC *Int.**	0.042	0.016	0.067	p = .001 (0.70)
AC *Int.* vs. AC *Post**	-0.048	-0.073	-0.023	p < .001 (0.83)
PC *Prae* vs. PC *Post*	-0.064	-0.130	0.001	p = .057 (0.41)
CC *Prae* vs. CC *Post**	-0.026	-0.047	-0.005	p = .010 (0.51)
AC *Int.* vs. PC *Int.**	-0.068	-0.116	-0.021	p = .003 (0.61)
AC *Int.* vs. CC *Int.**	-0.064	-0.101	-0.027	p < .001 (0.72)
AC *Post* vs. CC *Post**	-0.031	-0.061	-0.001	p = .042 (0.40)

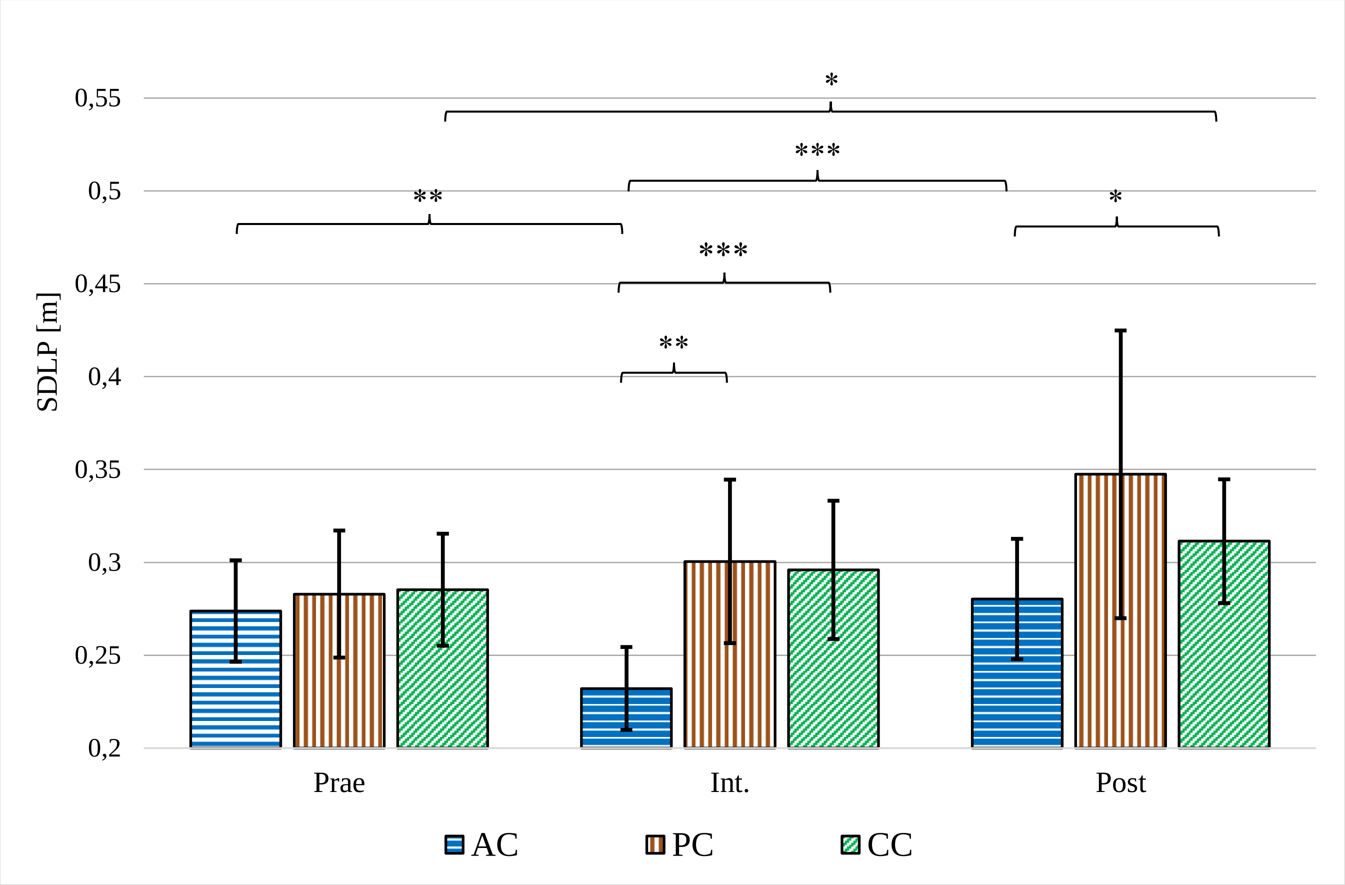

Figure 32: *Bar plot showing the mean SDLP of all subjects in the conditions. Whiskers indicate the lower and upper bounds of the 95% confidence interval. Statistically significant differences are highlighted with: * p < .05; ** p < .01; *** p < .001.*

7.3.2.2 Mean departure from lane

As illustrated in Figure 33 and 34, MDFL increased over time in the PC and the CC but not in the AC. On closer inspection, the MDFL in the CC increased from *Prae* to *Int.* and then remains at the same

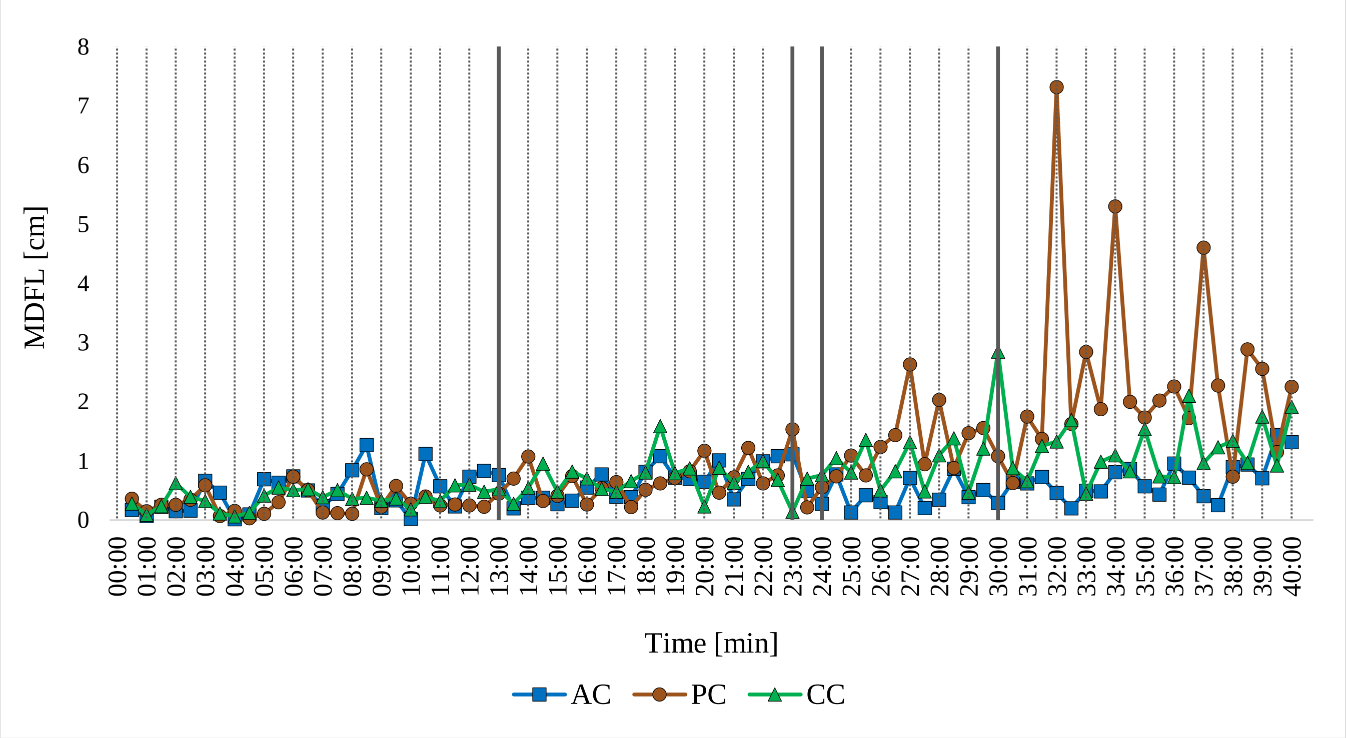

Figure 33: *Development of mean departure from lane in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

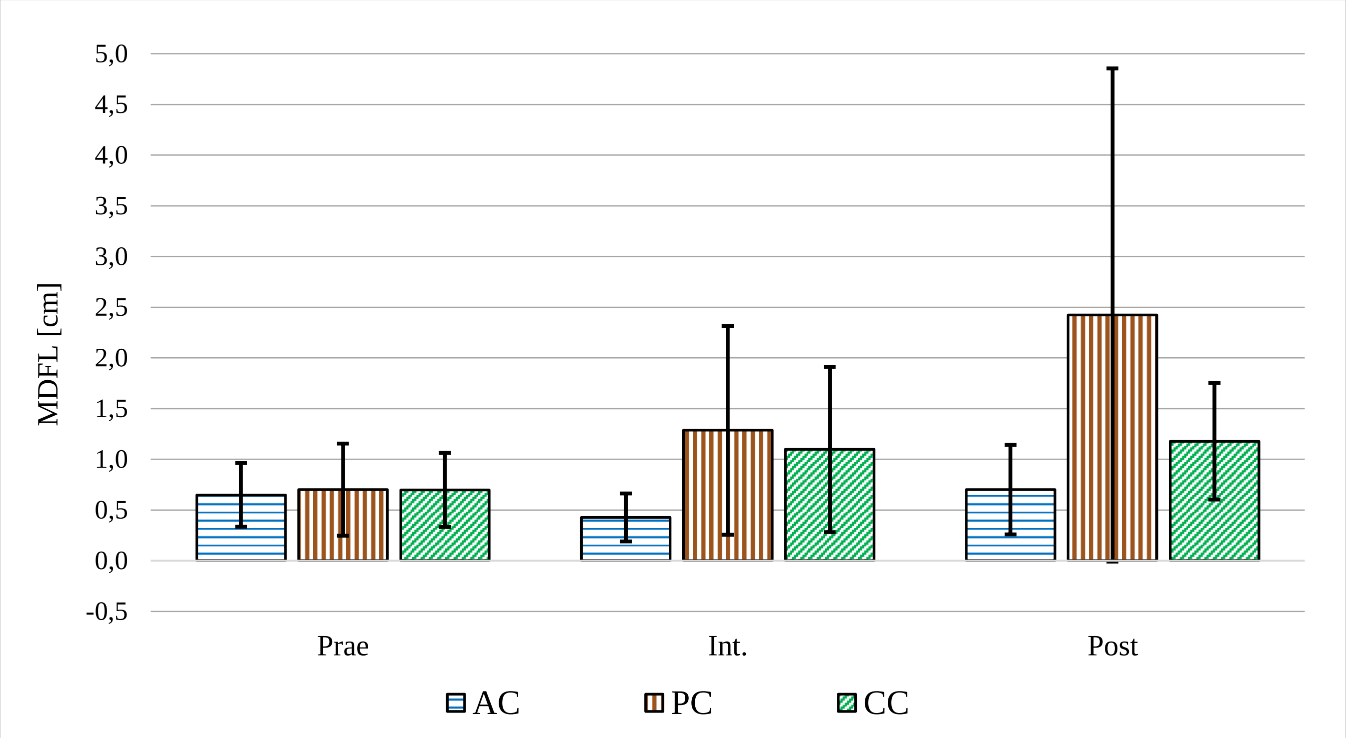

Figure 34: *Bar plot showing the mean MDFL in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

level. In the PC, MDFL increased constantly from *Prae* over *Int.* to *Post*. The highest mean value was found in the PC during *Post*.

The ANOVA revealed only a significant main effect for time interval. However, despite large mean differences between the variables, none of the pairwise comparisons revealed a significant difference. A descriptive follow-up analysis showed that two subjects largely caused the high MDFL values in the PC in *Post* with 40.05 and 15.65 cm.

7.3.2.3 Standard deviation of steering angle

Figure 35 and 36 show that the SDSA increased constantly over time in the PC and the CC. With the start of the MS (24:30 - 25:30 min) SDSA temporarily decreased in the PC. However, overal, SDSA also increased during the massage, just as during time interval *Int.* in the other conditions. Afterwards, during time interval *Post*, SDSA significantly decreased in the AC. SDSA peaked during the end of the IASS (29:30 – 30:30 min) which corresponds to the second shoulder sequence. During this sequence, the left and the right air bladders are alternately inflated at high pace (see Chapter 4.2.2). The high values within the first 30 seconds in all conditions were most likely caused by the acceleration maneuver at the beginning during which the vehicle had to be kept in the lane. Therefore, they can be considered irrelevant for the research question.

The ANOVA revealed a significant main effect for time interval, but not for condition. In addition, a significant interaction effect was found.

As depicted in Figure 36 and Table 17, in the CC, SDSA significantly increased over time from *Prae* to *Int.* and from *Prae* to *Post*. In the PC, SDSA increased over time from *Prae* to *Post* and from *Int.* to *Post*. Contrary effects occurred in the AC; SDSA decreased significantly from *Int.* to *Post*.
Significant differences between conditions were only found in time interval *Post*. SDSA was significantly lower in the AC compared to the PC and the CC. A medium effect size was found for all significant comparisons.

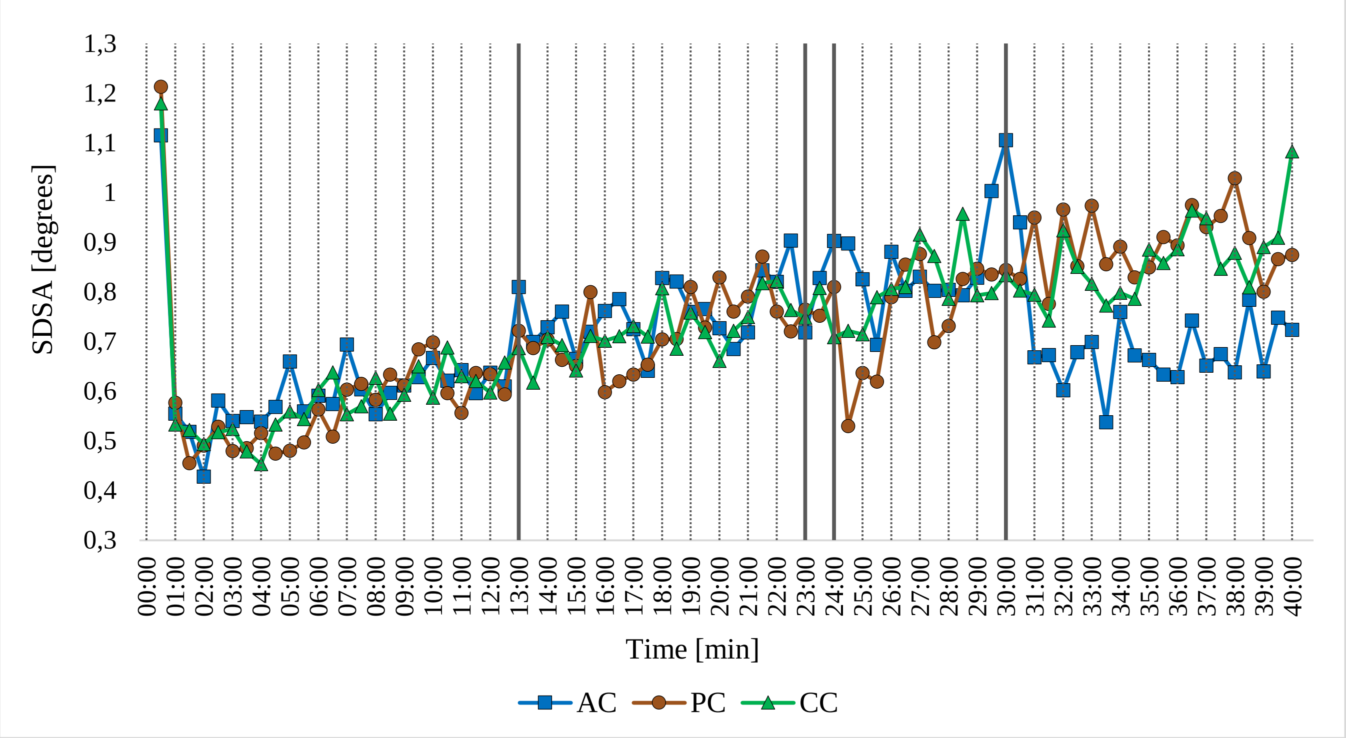

Figure 35: *Development of standard deviation of steering angle in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

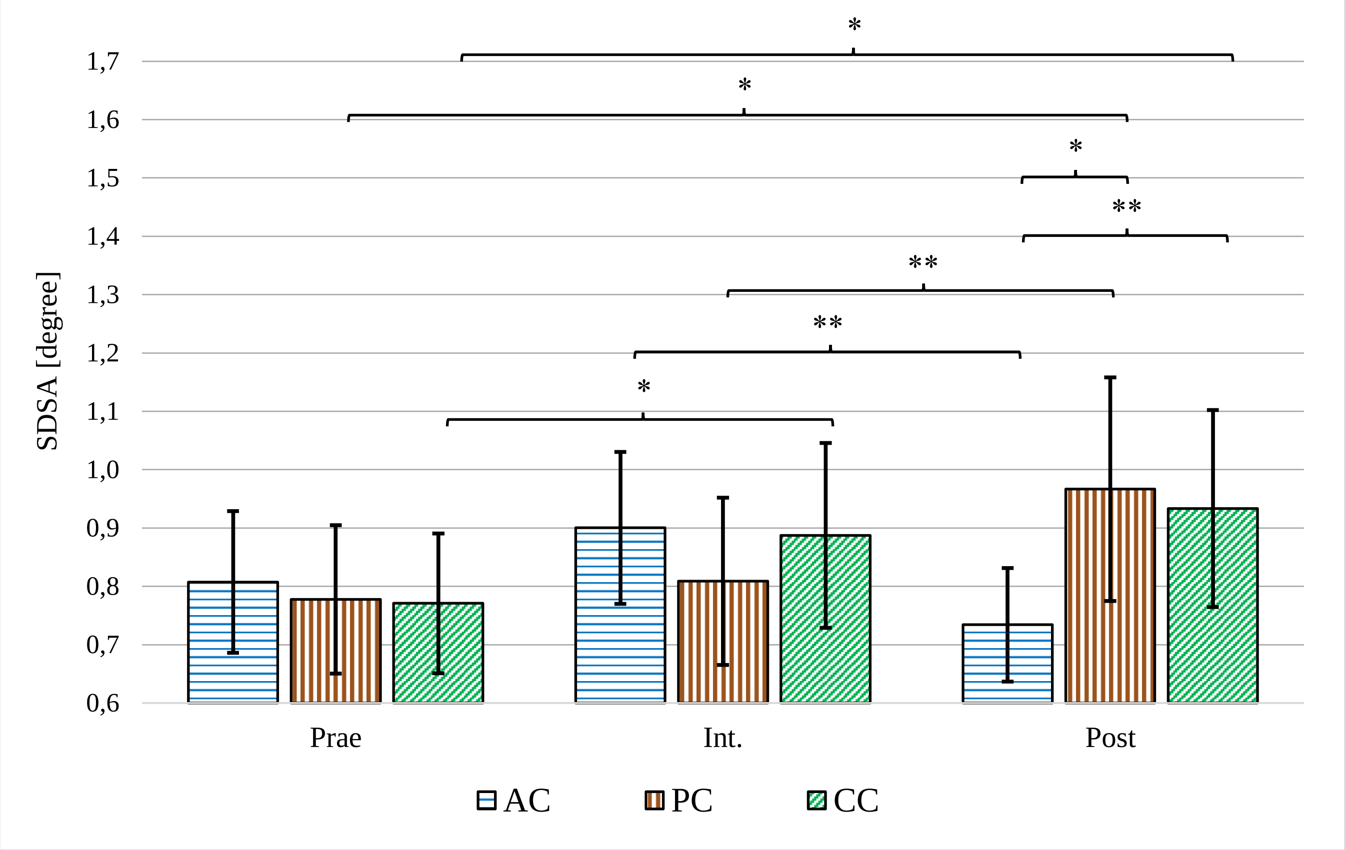

Figure 36: *Bar plot showing the mean SDSA in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

Table 17: *Post hoc comparisons for SDSA. Comparisons are listed with p < .06 and additionally marked with * if they were significant (p < .05).*

Compare	Mean difference	95% CI		Sig. (| *d* |)
		Lower	Upper	
AC *Int.* vs. AC *Post*	0.17	0.06	0.27	p = .001 (0.67)
PC *Int.* vs. PC *Post*	-0.16	-0.27	-0.05	p = .003 (0.61)
PC *Prae* vs. PC *Post*	-0.19	-0.32	-0.06	p = .003 (0.60)
CC *Prae* vs. CC *Int.*	-0.12	-0.21	-0.02	p = .014 (0.51)
CC *Prae* vs. CC *Post*	-0.16	-0.26	-0.06	p = .001 (0.70)
AC *Post* vs. PC *Post*	-0.23	-0.40	-0.07	p = .003 (0.60)
AC *Post* vs. CC *Post*	-0.20	-0.37	-0.03	p = .016 (0.50)

7.3.3 Vital parameters

Similar to the simulator data, the vital data was analyzed using a 3 x 3 two-way repeated-measures MANOVA. The dependent variables were the vital parameters HR, HRV and SCL. The two independent variables were time interval (Prae/Int./Post) and condition (AC/PC/CC). Thirty-two subjects were included in the analyses because three datasets showed noisy or anomalous signals. As can be seen in Table 18, the MANOVA revealed a significant main effect for time interval and condition as well as a significant interaction effect. Therefore, a univariate 3 x 3 two-way repeated measures ANOVA was then calculated for each of the dependent variables. The two independent variables were time interval (Prae/Int./Post) and conditions (AC/PC/CC). In the section of each parameter the results of the ANOVAs are reported in short, detailed values are listed in Appendix D. Additionally, in the section of each parameter a figure is included, which illustrates the mean values and variances in the different conditions and time intervals. A table with exact values can be found in Appendix E.

Table 18: *Results of the MANOVA for the analysis of driving simulator data.*

	Pilla's trace	F	Df_1	Df_{error}	Sig.	Partial η^2
TI	.73	11.70	6	26	p < .001	.73
Condition	.43	3.26	6	26	p = .016	.43
TI * cond.	.77	5.71	12	20	p < .001	.77

7.3.3.1 Heart rate

As shown in Figure 37 and 38, heart rate increased over time within all conditions. In the AC, a sharp increase of HR occurred with the beginning of the introduction (23:00 min). The heart rate steadily increased within *Int.* and quickly dropped after the use of the IASS. With the beginning of the MS in the PC, the heart rate temporarily decreased, but increased back to the initial level by the end of *Int.* In the CC, the heart rate increased constantly.

These observations are also reflected in the statistical analysis. The ANOVA revealed a significant main effect for time interval and condition as well as a significant interaction effect.

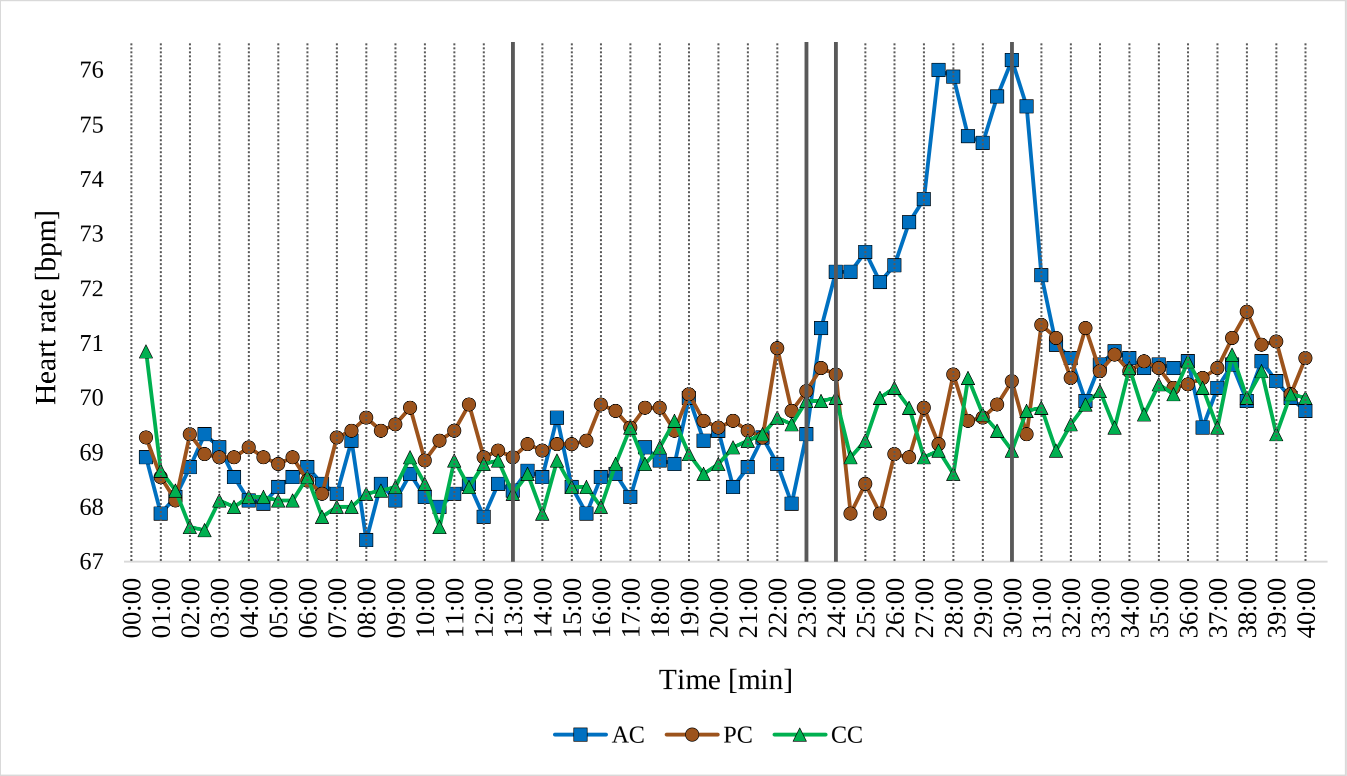

Figure 37: *Development of heart rate in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

As reflected by Figure 38 and Table 19, the heart rate increased significantly over time in all three conditions. In the AC and the CC, this was the case from *Prae* to *Post*, and in the PC from *Int.* to *Post*. Additionally, the heart rate during the AC was significantly higher in *Int.* compared to *Prae* and *Post*.

Significant differences between conditions were only found during *Int.*, with a significantly higher heart rate in the AC compared to the PC and the CC.

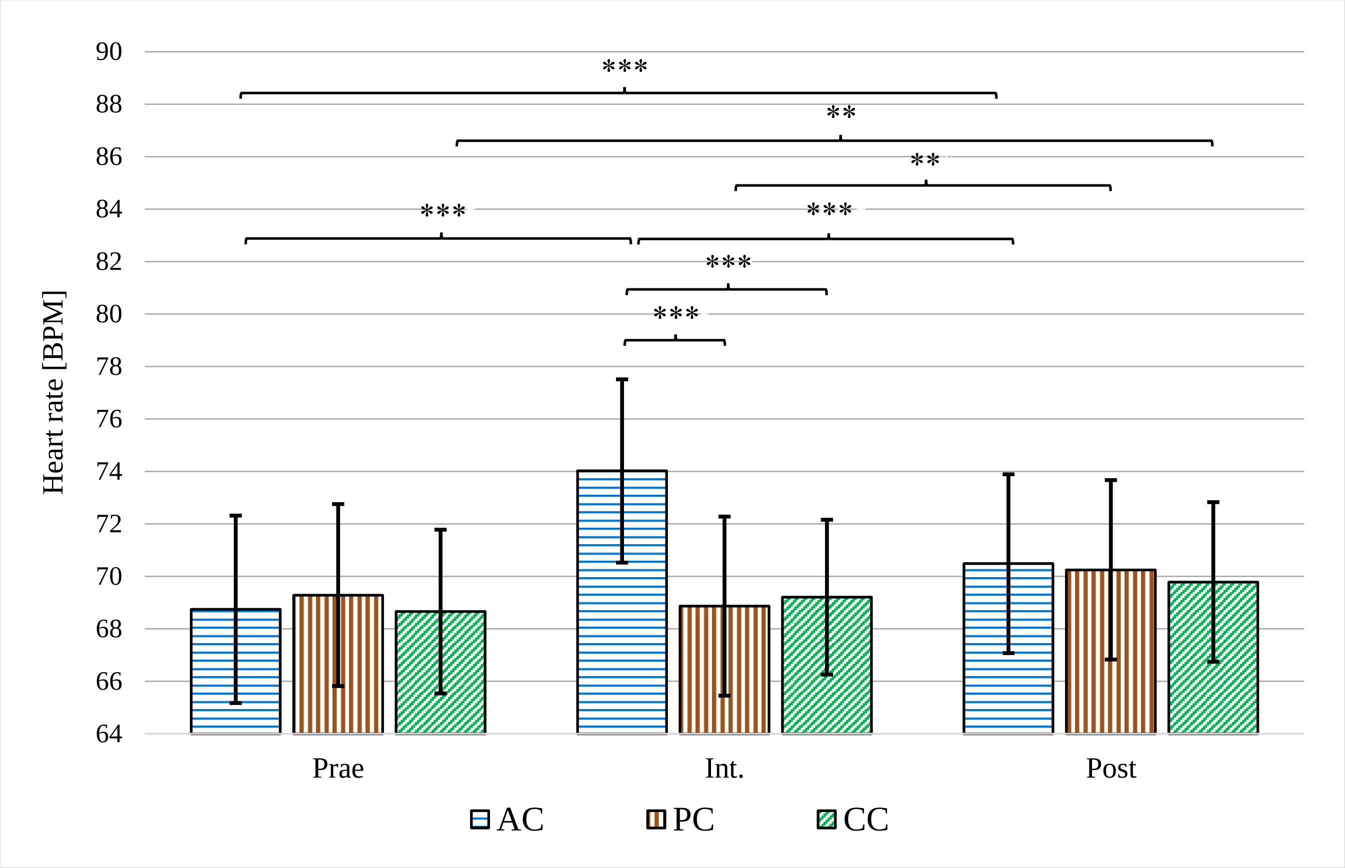

Figure 38: *Bar plot showing the mean heart rate in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

Table 19: *Post hoc comparisons for heart rate. Comparisons are listed with p < .06 and additionally marked with * if they were significant (p < .05).*

Compare	Mean difference	95% CI Lower	95% CI Upper	Sig. (| *d* |)
AC *Prae* vs. AC *Int.*	-5.3	-7.1	-3.4	p <.001 (1.26)
AC *Int.* vs. AC *Post*	3.5	1.9	5.2	p <.001 (0.96)
AC *Prae* vs. AC *Post*	-1.7	-2.7	-0.8	p <.001 (0.84)
PC *Int.* vs. PC *Post*	-1.4	-2.3	-0.4	p = .003 (0.64)
CC *Prae* vs. CC *Post*	-1.1	-1.8	-0.4	p = .001 (0.71)
AC *Int.* vs. PC *Int.*	5.2	2.7	7.6	p < .001 (0.94)
AC *Int.* vs. CC *Int.*	4.8	2.9	6.8	p < .001 (1.11)

7.3.3.2 Heart rate variability

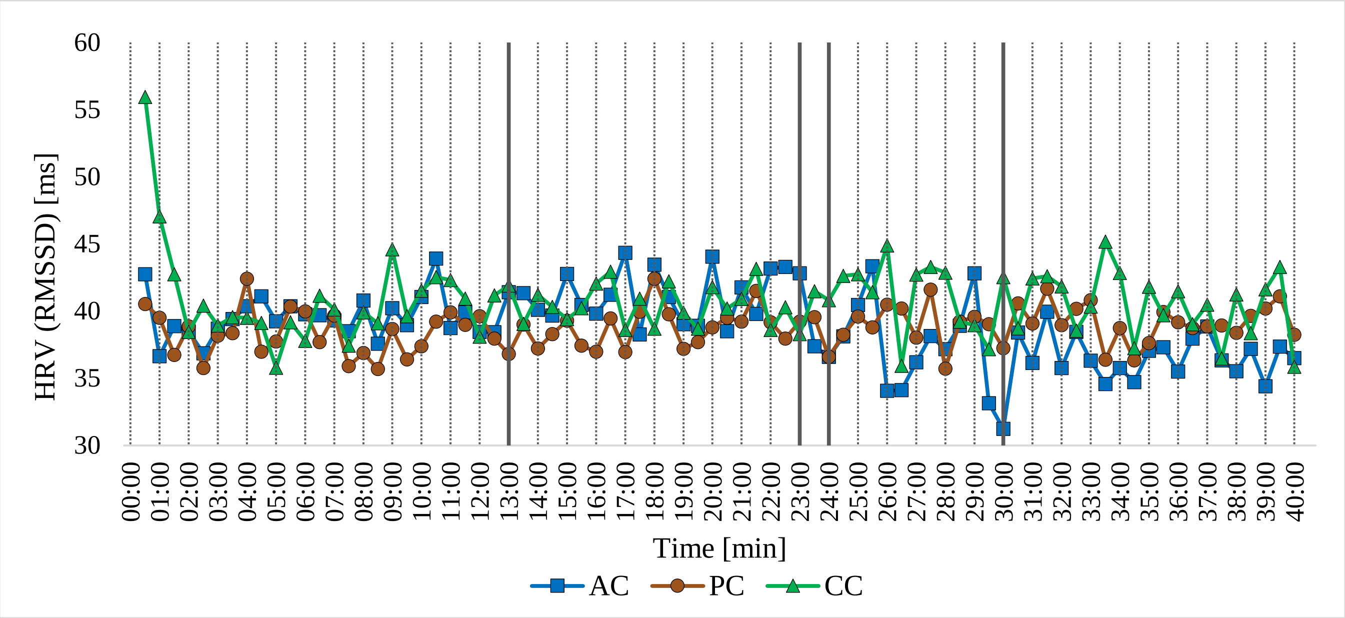

Figure 39: *Development of heart rate variability in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

As depicted in Figure 39, heart rate variability did not show any systematical changes over time in any of the conditions. The ANOVA revealed no significant main effect for condition or intervention, and no significant interaction effect. This is also reflected by the mean values (see Figure 40).

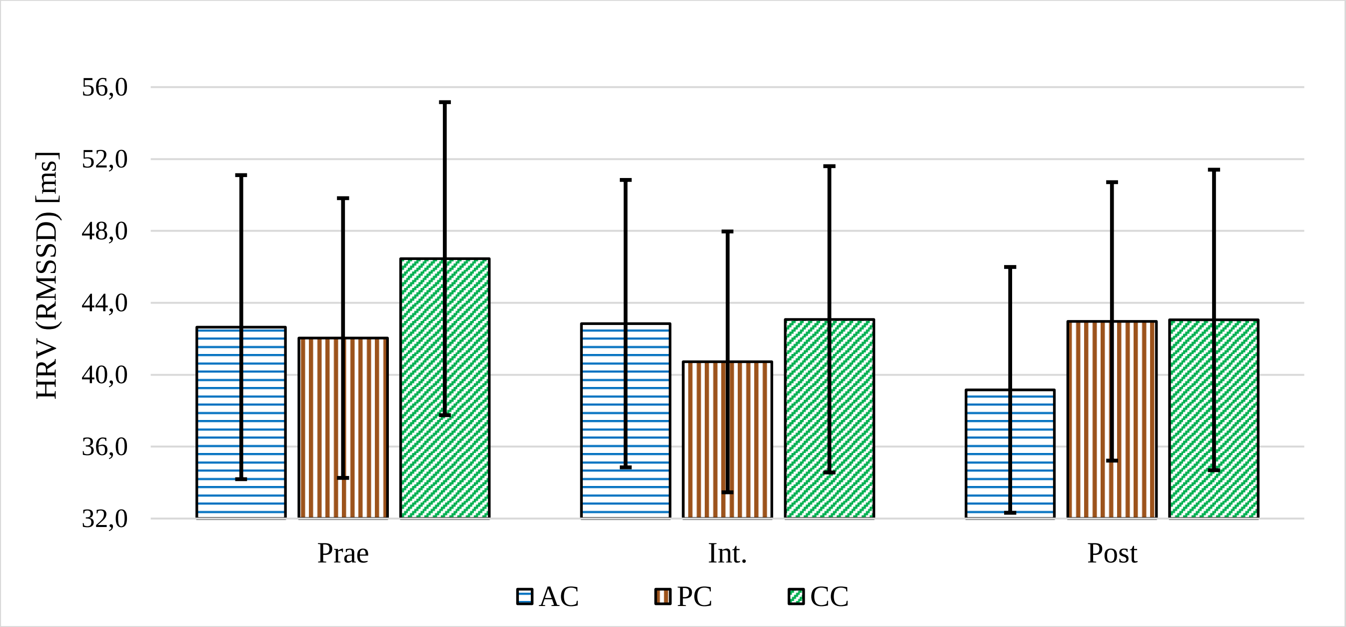

Figure 40: *Bar plot showing the mean heart rate variability in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

7.3.3.3 Skin conductance level

Figure 41 depicts the SCL over the course of the study. In the beginning of all three conditions, the SCL decreased until 6:00 - 9:00 min. Afterwards the SCL increased again in all conditions. Clear differences between conditions occurred with the beginning of the introductions. With the start of the introduction in the AC (24:01 min), the SCL increased sharply and remained on this level until the end of the IASS (30:09 min). After *Int.*, SCL in the AC decreased steadily over time, markedly below the values in the CC. With the beginning of the introduction in the PC (23:49 min), SCL fluctuated stronger than before; but kept a largely similar pattern to the CC. That means both in the PC and the CC, SCL increased roughly linear with time.

The statistical analysis partially reflects these observations. The ANOVA revealed a significant main effect for time interval but not for condition. Additionally, a significant interaction effect was found.

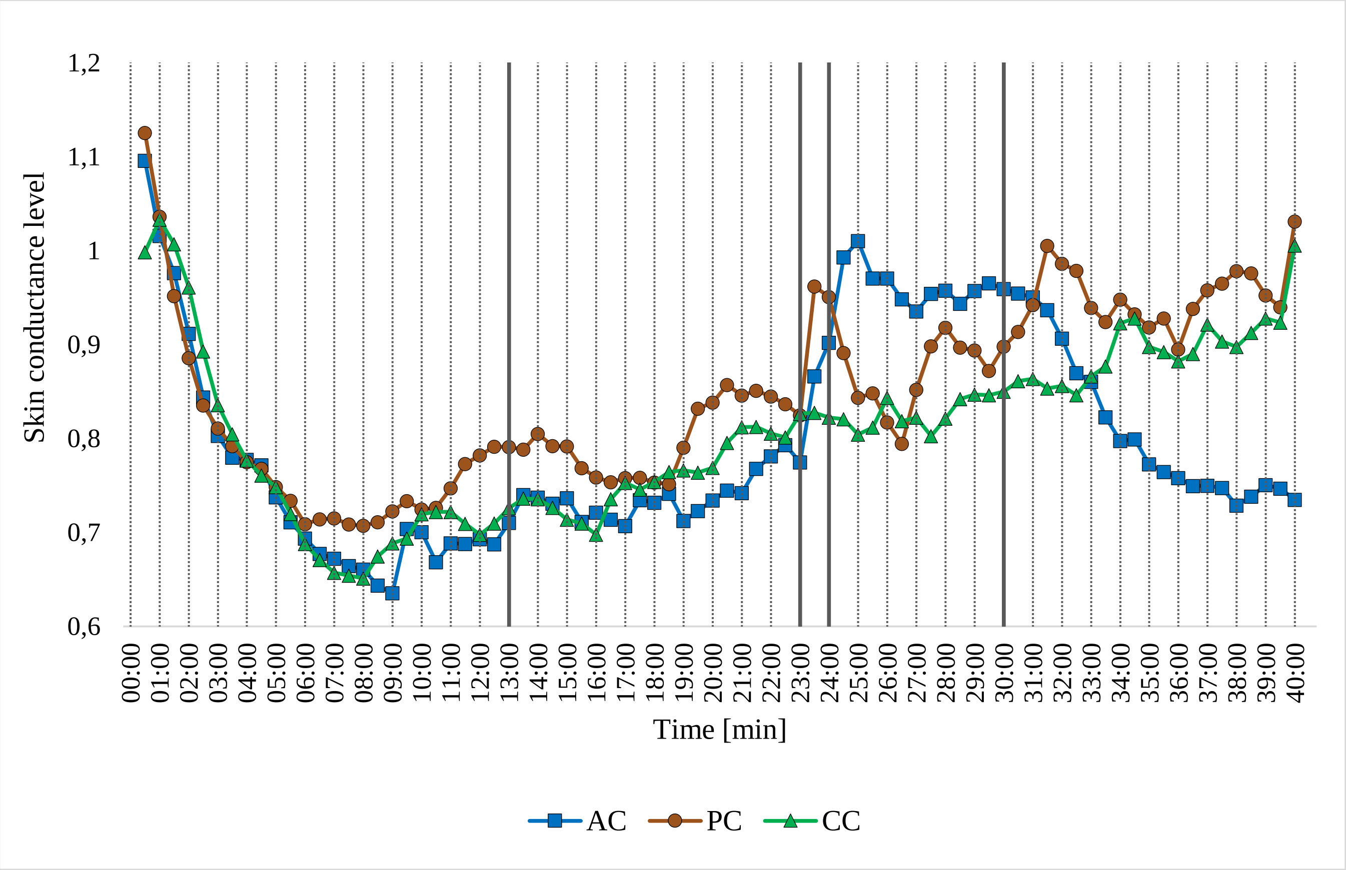

Figure 41: *Development of skin conductance in the conditions. Since a ratio of skin conductance was calculated for normation (see Chapter 7.2.2) no unit is given. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

As shown in Table 20 as well as Figure 42, significant differences occurred only within the AC and CC. In the AC, SCL was significantly higher in *Int.*, compared to *Prae* and *Post*. In the CC, SCL increased over time and shows significant differences between the three time intervals.

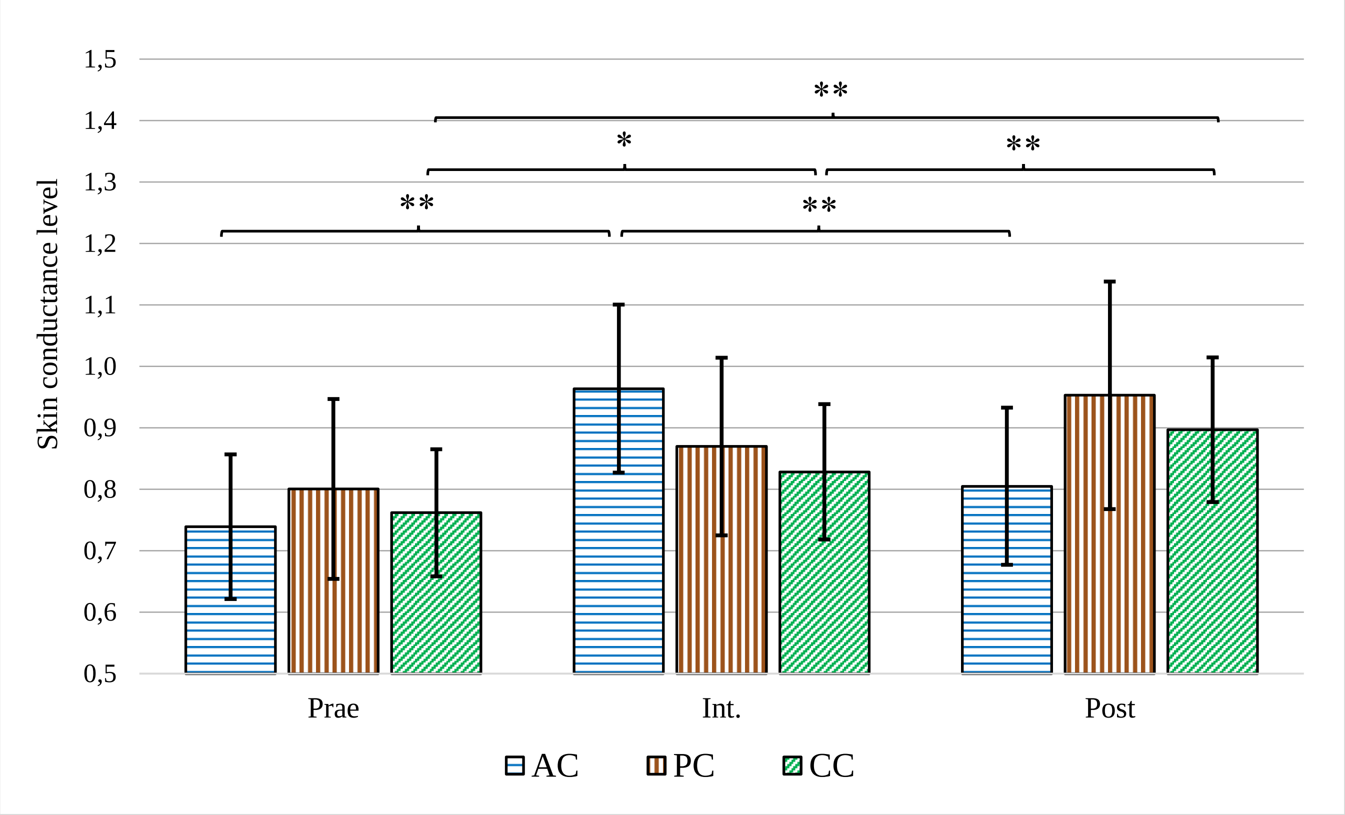

Figure 42: *Bar plot showing the mean skin conductance level in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

Table 20: *Post hoc comparisons for skin conductance level. Comparisons are listed with p < .06 and additionally marked with * if they were significant (p < .05).*

Compare	Mean Difference	95% CI		Sig. (| *d* |)
		Lower	Upper	
AC *Prae* vs. AC *Int.*	-0.23	-0.38	-0.07	p = .003 (0.65)
AC *Int.* vs. AC *Post*	0.16	0.05	0.27	p = .002 (0.67)
CC *Prae* vs. CC *Int.*	-0.07	-0.13	0.00	p = .044 (0.46)
CC *Int.* vs. CC *Post*	-0.14	-0.23	-0.04	p = .004 (0.57)
CC *Prae* vs. CC *Post*	-0.07	-0.12	-0.02	p = .008 (0.63)

7.3.4 Eye tracking parameters for measuring passive driver fatigue

Similar to Chapter 7.3.2 and 7.3.3 the eye tracking data to measure passive driver fatigue was analyzed using a 3 x 3 two-way repeated-measures MANOVA. The dependent variables were the eye tracking parameters ED, BF and BD. The two independent variables were time interval (Prae/Int./Post) and condition (AC/PC/CC). Due to storage problems in two subjects, thirty-three datasets were included in the analysis. As can be seen in Table 21, the MANOVA revealed a significant main effect for time interval and condition. Under a strict assumption there was no significant interaction effect with p = .052. However, because this value just marginally misses the significance level of .05, and the conclusions are drawn with the subsequent ANOVAS, the assumption was made, that a significant interaction effect exists as well. In the section of each parameter the results of the ANOVAs are reported in short, detailed values are listed in Appendix D Additionally, in the section of each parameter a figure is included, which illustrates the mean values and variances in the different conditions and time intervals. A table with exact values can be found in Appendix E.

Table 21: *Results of the MANOVA for the analysis of the eye tracking data to measure PDF.*

	Pilla's trace	F	Df_1	Df_{error}	Sig.	Partial η^2
TI	.48	4.14	6	27	p = .005	.48
Condition	.49	4.29	6	27	p = .004	.49
TI * cond.	.56	2.23	12	21	p = .052	.56

Therefore, a univariate 3 x 3 two-way repeated measures ANOVA was then calculated for each of the dependent variables. The two independent variables were time interval (Prae/Int./Post) and conditions (AC/PC/CC).

7.3.4.1 Eyelid distance

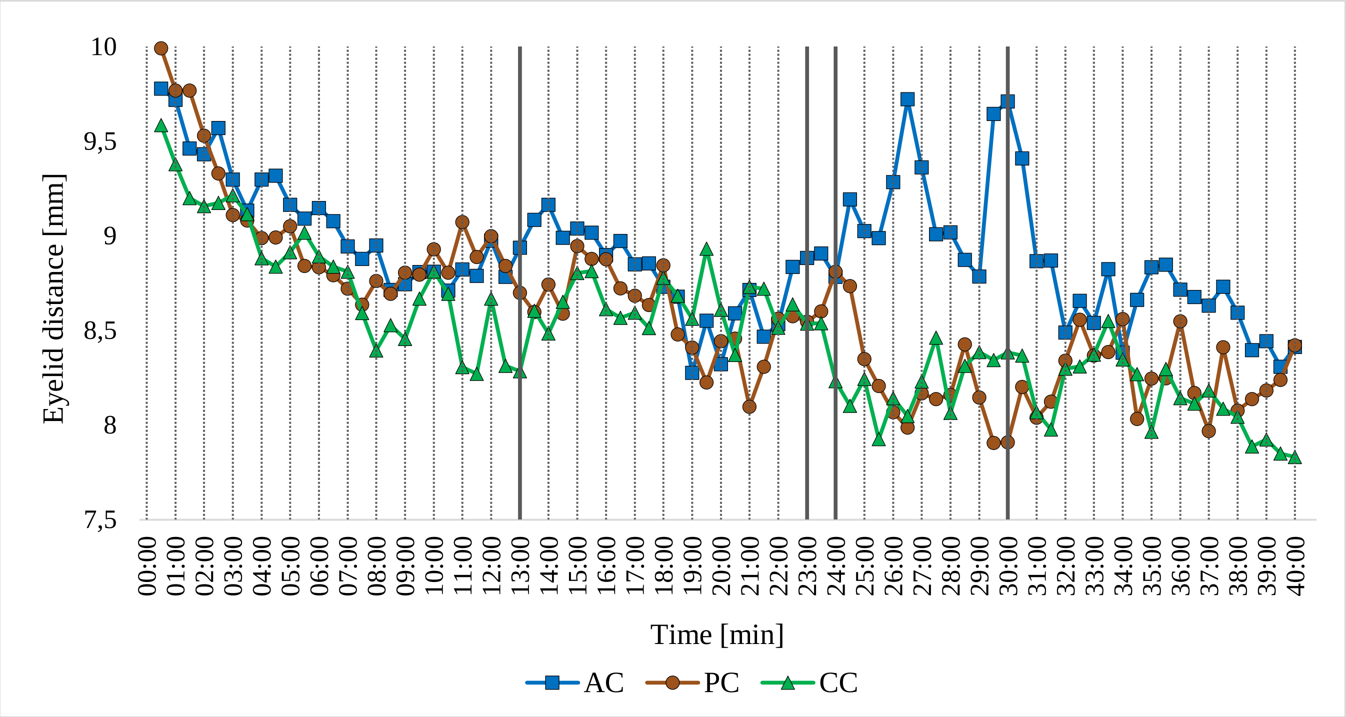

Figure 43: *Development of eyelid distance in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

Figure 43 shows that the eyelid distance decreased over time in all conditions. The pattern was similar in the PC and the CC. Contrarily, the eyelid distance increased sharply with the beginning of *Int.* in the AC (24:01 min). During the use of the IASS, two peaks are observable between 25:30 – 27:00 min and 29:00 – 30:30 min. These periods related to the shoulder sequences that lasted from 25:34 - 26:58 and 29:03 - 30:09 min. After the use of the IASS (from 30:09 min), SCL decreased again to a level that is just above the PC and the CC.

The statistical analysis reflects these observations. The ANOVA revealed a significant main effect for condition and intervention, as well as a significant interaction.

As shown in Figure 44 and Table 22, significant comparisons within conditions were only found for the AC and the PC. In the AC, eyelid distance was significantly higher during *Int.* compared to *Prae* and *Post*. In the PC, eyelid distance significantly decreased over time from *Prae* to *Int.* as well as from *Prae* to *Post*.

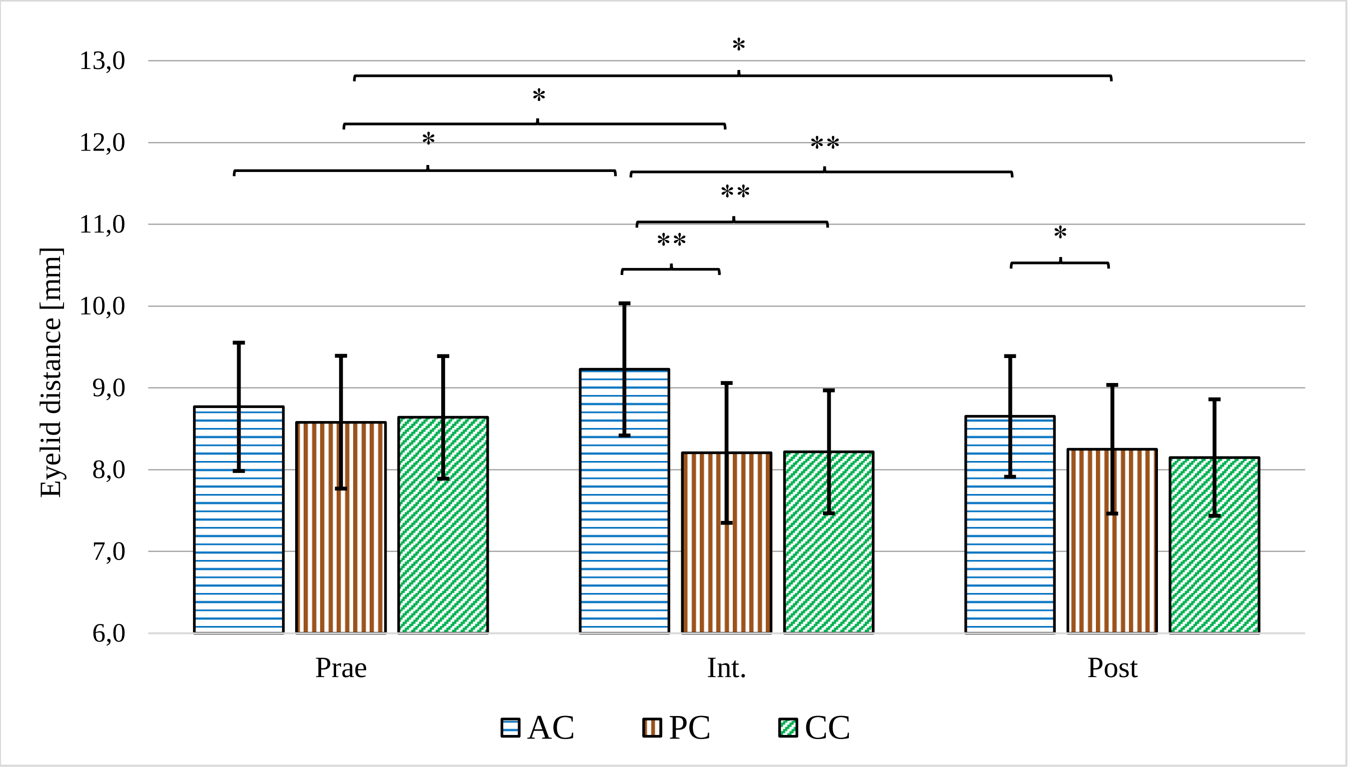

Figure 44: *Bar plot showing the mean heart rate variability in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

The comparison between conditions showed that during *Int.*, eyelid distance was significantly larger in the AC compared to the PC and the CC. In *Post*, eyelid distance was significantly larger in the AC than in the PC. Regarding the mean values, eyelid distance was also larger in the AC compared to the CC, however, significance was just missed with p = .053.

Table 22: *Post hoc comparisons for skin conductance level. Comparisons are listed with p < .06 and additionally marked with * if they were significant (p < .05).*

Compare	Mean difference	95% CI		Sig. (| *d* |)
		Lower	Upper	
AC *Prae* vs. AC *Int.*	-0.46	-0.89	-0.02	p = .037 (0.46)
AC *Int.* vs. AC *Post*	0.57	0.19	0.96	p = .002 (0.65)
PC *Prae* vs. PC *Int.*	0.37	0.02	0.73	p = .033 (0.47)
PC *Prae* vs. PC *Post*	0.33	0.03	0.63	p = .026 (0.49)
AC *Int.* vs. PC *Int.*	1.02	0.35	1.69	p = .002 (0.67)
AC *Int.* vs. CC *Int.*	1.01	0.35	1.67	p = .002 (0.67)
AC *Post* vs. PC *Post*	0.40	0.01	0.79	p = .040 (0.46)
AC *Post* vs. CC *Post*	0.51	-0.01	1.02	p = .053 (0.44)

7.3.4.2 Blink frequency

Figure 45 and 46 show that no clear patterns of blink frequency occurred within the course of the study in any condition. Solely with beginning of the introductions in the AC and the PC, the blink frequency increased, which lasted for around two minutes until approximately 25:00 min. These findings are in line with the results of the statistical analysis. The ANOVA revealed no significant comparisons.

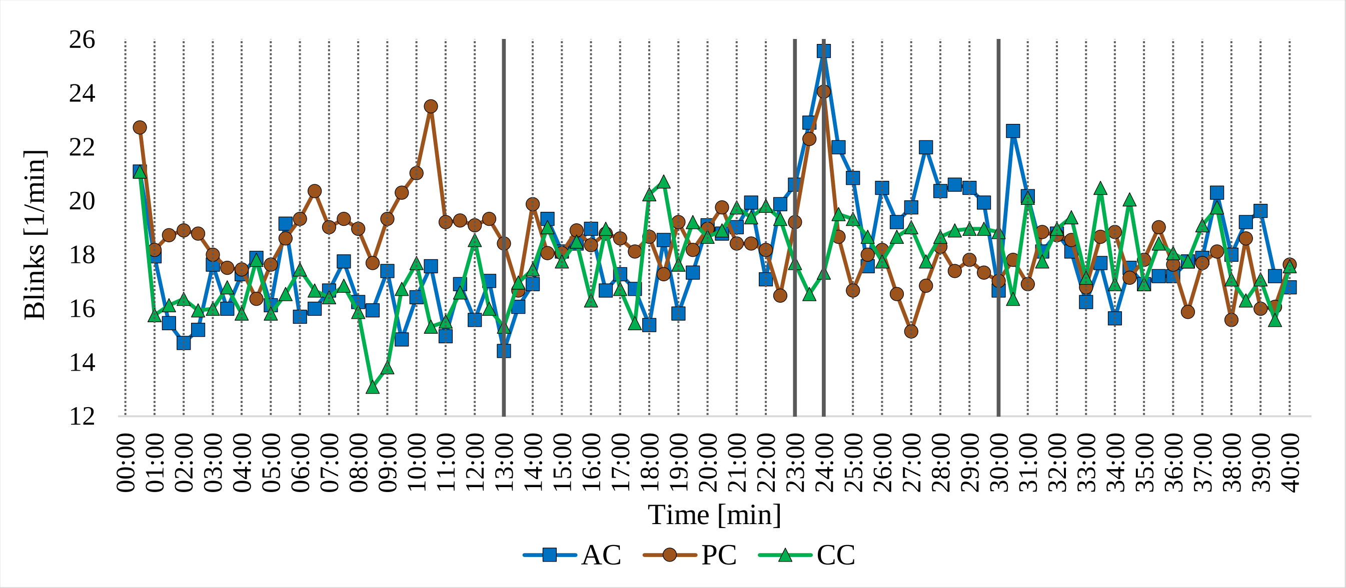

Figure 45: *Development of blink frequency in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

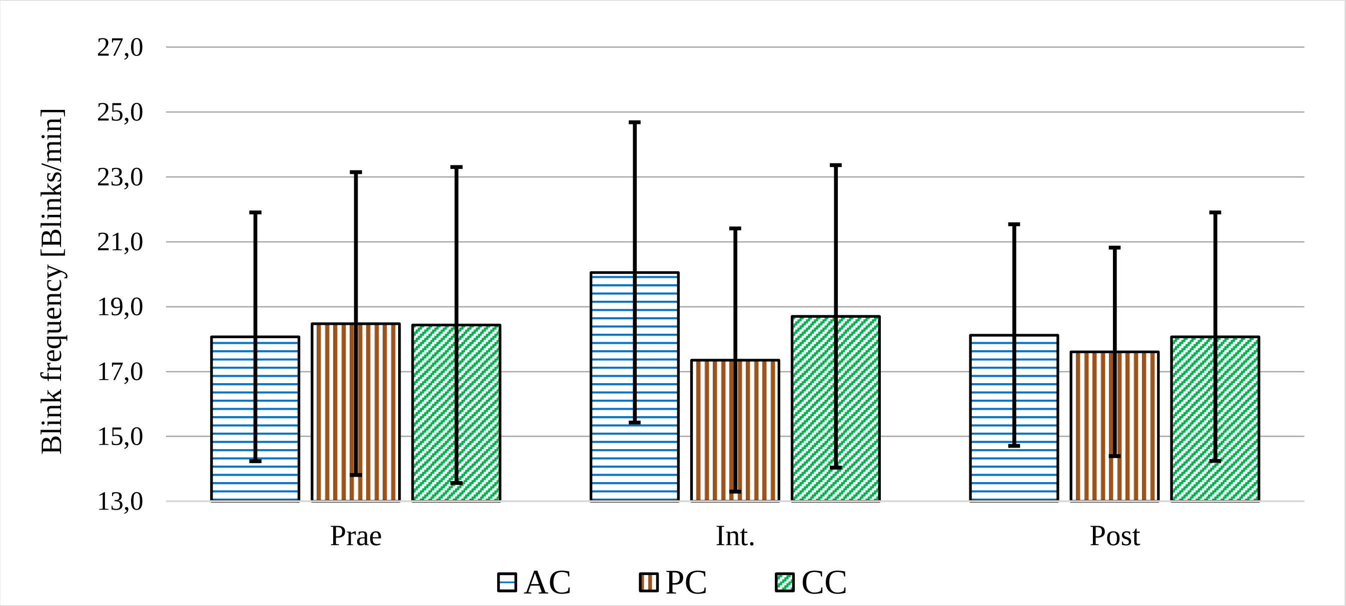

Figure 46: *Bar plot showing the mean blink frequency in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

7.3.4.3 Blink duration

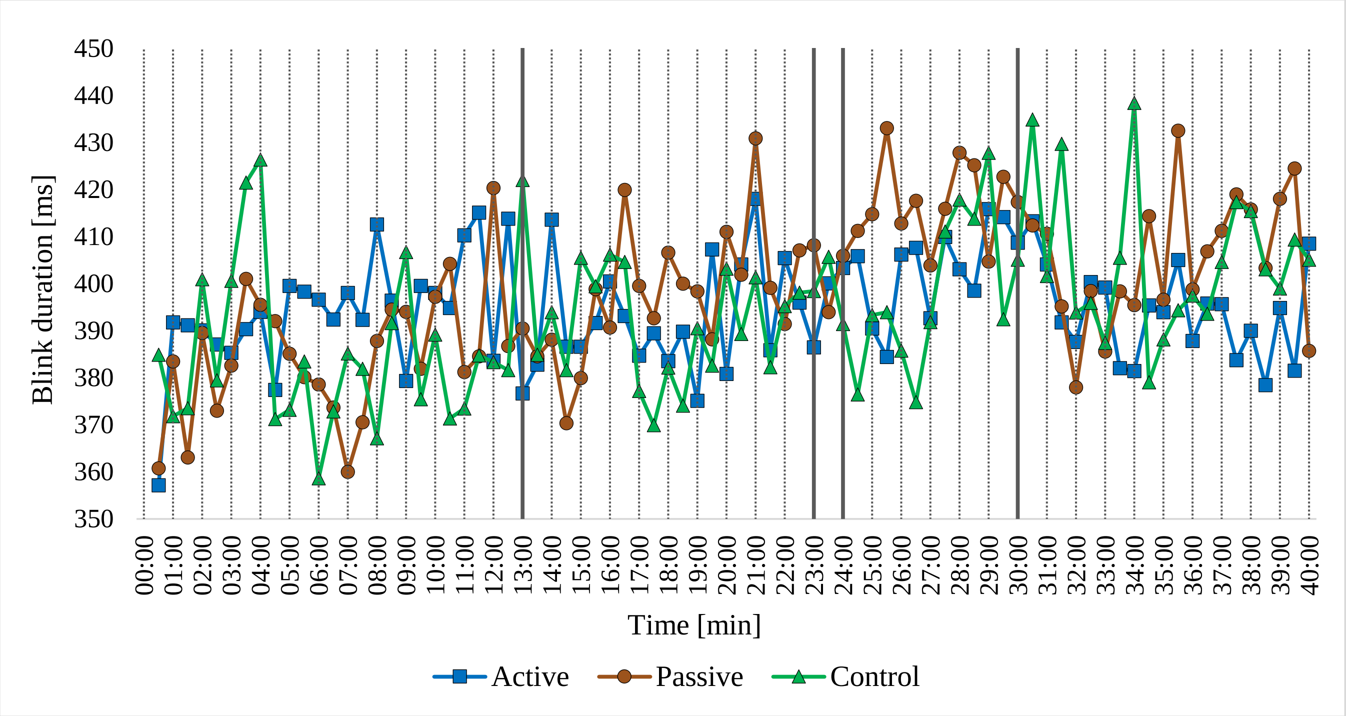

Figure 47: *Development of blink duration in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

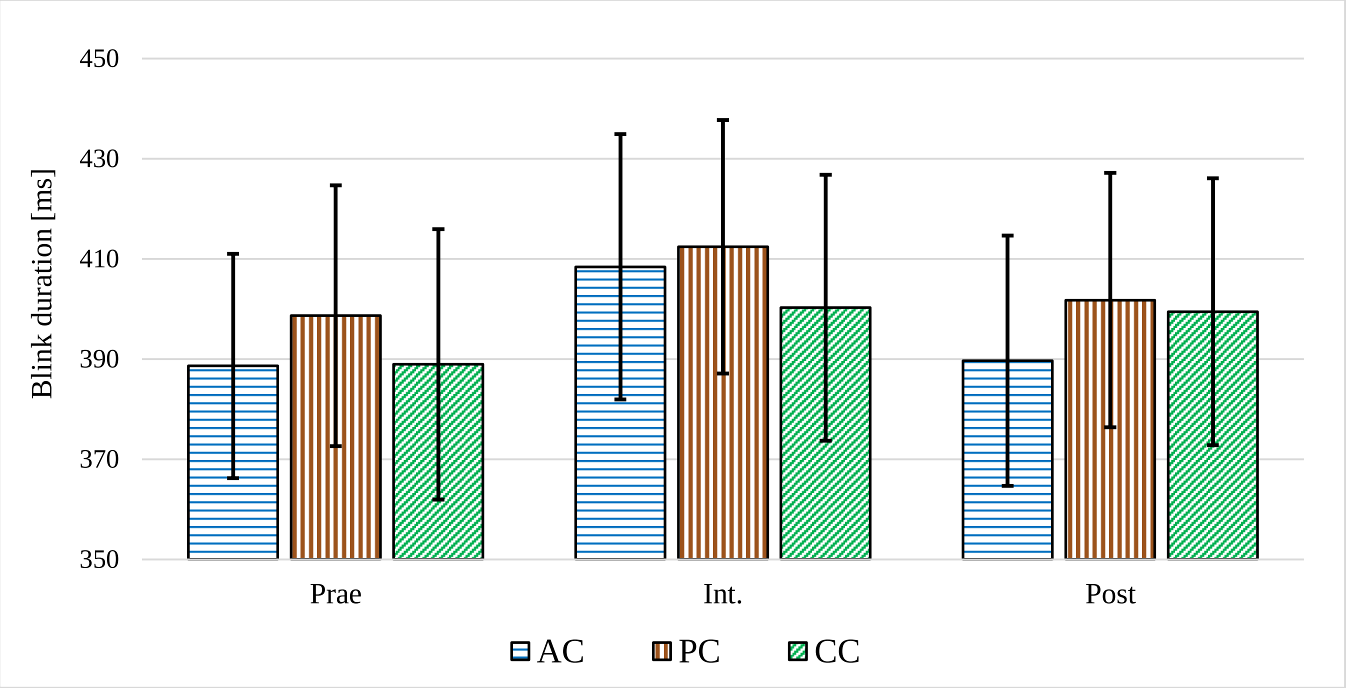

Figure 48: *Bar plot showing the mean blink duration in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

Figure 47 and 48 show that blink duration increased in all conditions over time with the highest values in *Int*. Figure 47 shows, however, that the gradient is very low in comparison to the fluctuations between the 30-second intervals. Apart from that, no systematic changes were found in any of the conditions. The ANOVA revealed only a significant main effect for time interval. However, post-hoc comparisons revealed no significant differences for any of the comparisons.

7.3.5 Pupil diameter for measuring task complexity

Pupil diameter was measured to draw conclusions about task complexity. As shown in Figure 49 and 50, the pupil diameter (PD) was quite similar and largely unaffected throughout the study in the AC and the CC. This was also the case in the PC until the end of time interval *Prae*. With beginning of time interval *Int.*, the pupil size started to increase and remained on this elevated level until 35:30 min.

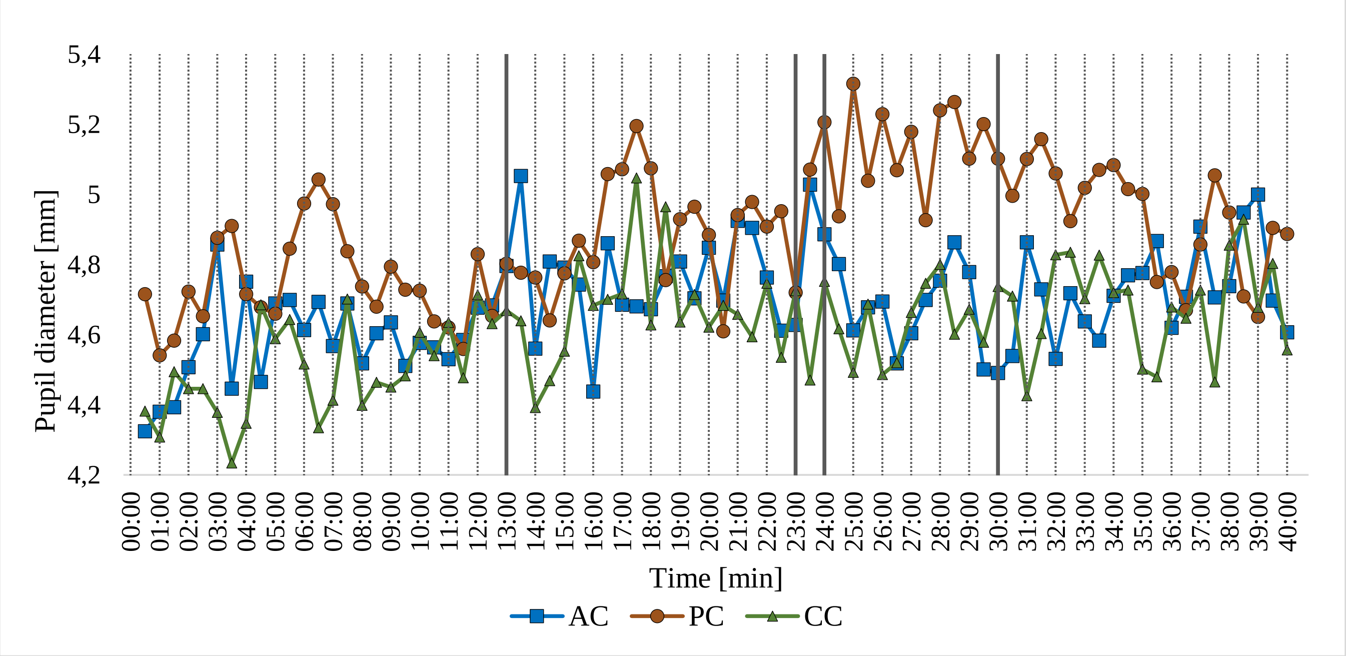

Figure 49: *Development of pupil diameter in the conditions. Please refer to the description of Figure 31 for more detailed information on the layout of the figure.*

Equivalent to the other eye tracking parameters, pupil diameter was analyzed using a univariate 3 x 3 two-way repeated measures ANOVA, with the independent variables time interval (Prae/Int./Post) and condition (AC/PC/CC). The ANOVA revealed no significant effects, even though the main effect for condition just missed significance with p = .057. Detailed values for the ANOVA are listed in Appendix

D. Exact mean values and variances in the different conditions and time intervals can be found in Appendix E.

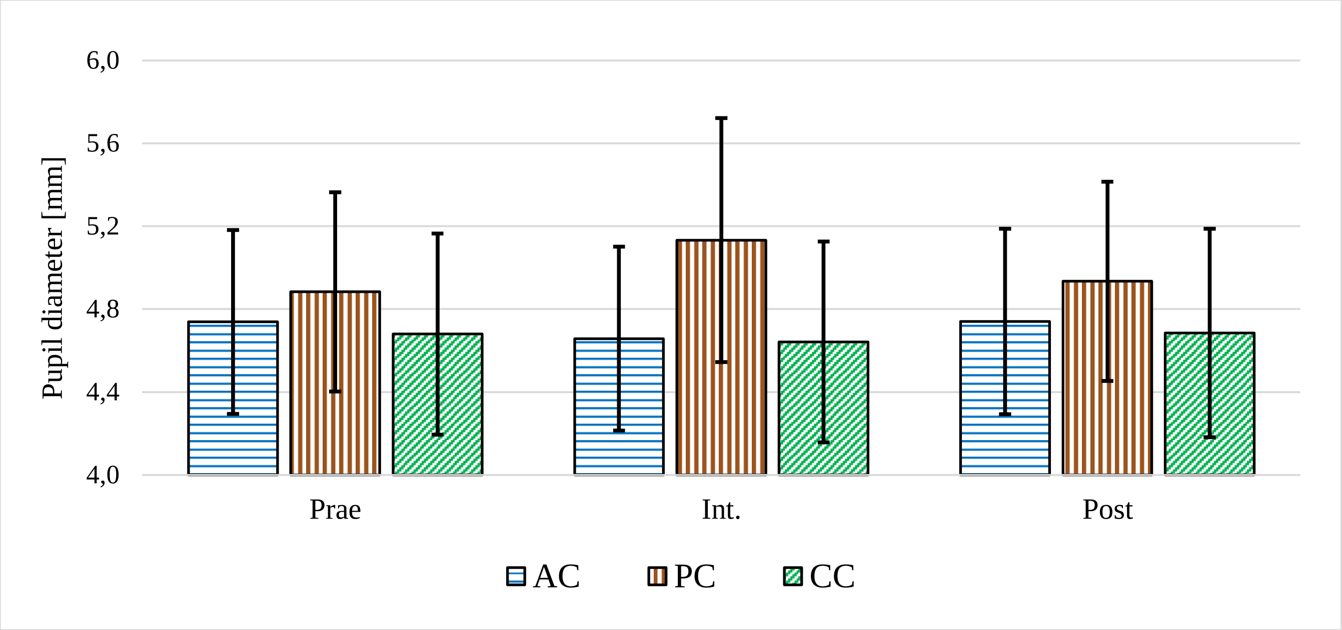

Figure 50: *Bar plot showing the mean pupil diameter in the conditions. Please refer to the description of Figure 32 for more detailed information on the layout of the figure.*

7.4 Discussion

The main contribution of the study was to investigate whether performing an additional motor task while driving inducted through the interactive seating system can counteract passive driver fatigue. For this, the IASS was compared to a state-of-the-art massage seating system and a control condition. The MS offers additional tactile stimuli whereas the IASS represents an additional motor task (see Chapter 2.5.2).

7.4.1 Subjective passive driver fatigue

Subjective fatigue, measured with the Karolinska sleepines scale increased in all the conditions with time, indicating that the study design generally caused passive driver fatigue. However, there were remarkable differences regarding the amplitude of the effect. That said, subjective fatigue increased significantly less in the active condition compared to the passive and control condition. No significant difference was found between the passive and the control condition. Therefore, only the IASS reduced subjective passive driver fatigue, while the MS did not.

7.4.2 Driving parameters

The increase of subjective PDF during the conditions is also reflected in the driving simulator data. Firstly, the SDLP significantly increased over time in the control condition. This trend was also observable for the passive condition; however, the comparison from *Prae* to *Post* just missed significance. The SDSA increased significantly over time both in the control and in the passive condition. In the active condition, nor SDLP neither SDSA increased significantly with time. This shows that only the IASS could reduce the impairment of lane keeping over time.

The same was found for the comparisons within time intervals. The IASS improved lane keeping compared to the PC and CC during and after the use, reflected by significantly lower values for SDLP and SDSA.

The findings that the beneficial effects of the IASS persisted after the use is an important improvement on the cognitive secondary task presented by Oron-Gilad et al. (2008). For the cognitive secondary task, alerting effects were only found during the use. However, the measurement period after the use of the IASS was quite short in this study with about 10 minutes. How long the effect actually lasts should be investigated in more detail in a real-world driving task. In comparison to real driving, PDF during simulator rides increases more quickly (Nilsson et al., 1997). This might conversely shorten the follow-up effect after the use of the IASS in the driving simulator.

An explanation why the MS did not lead to an improvement of PDF might be that the tactile stimuli are simple and task-independent. Thus, they might be quickly repetitive and habituated themselves. This aspect was also frequently noted by the subjects after the study and is discussed in the context of thermal stimulation by E. Schmidt & Bullinger (2019). A seating system quite similar to the MS was evaluated by Schneider et al. (2021). The hardware of both systems is largely equivalent, they only differ in the location of the air bladders as well as in their inflation times during the program. Schneider et al. (2021) found an alerting effect of the seating system, reflected by the alpha-spindle rate in the electroencephalogramm. However, the seating system did not show any improvement on subjective fatigue. The authors conclude that the questionnaire (KSS) was not sensitive enough to capture the alerting effects of the seating system. This indicates that the effects of the seating system on alertness might have been rather small. Unfortunately, no driving parameters were collected, so it remains open whether the seating system improves driving performance.

However, driving parameters were captured by S. Lee et al. (2020) in order to investigate the alerting effects of a motion seating system. The system activated coordinated but recurring motions of the backrest recline, cushion tilt, and lumbar support. The authors found a significant reduction of the standard deviation of velocity, PERCLOS and subjective PDF. However, they found no improvement on the lane keeping ability, reflected by the steering wheel rate, which is in line with the findings of the MS in this study.

In summary, based on this study, the IASS is clearly superior to the massage seating system in terms of reducing passive driver fatigue. Although alerting effects of passive dynamic seating systems were partially observed in the literature, these were not found for the massage seating system in this study. The most likely reason for the inconsistent effects of passive dynamic seating systems on PDF is that tactile stimuli might become monotonous themselves. Consequently, the tactile stimuli should be designed as variably as possible, if passive dynamic seating systems are used as anti-fatigue devices. In the future, one could for example combine a motion seating system with inflatable massage bladders, or offer new tactile stimuli, e.g. through vibrating elements.

In detail, the measurement of SDSA also revealed a potential optimization for the IASS. During the use of the IASS the SDSA was descriptively (not significantly) higher in comparison to the passive and control condition. In detail, SDSA peaked during the second shoulder sequence (see Figure 35). During this sequence, the left and the right air bladders are alternately inflated at high pace (see Chapter 4.2.2). This might have affected the steering frequency. However, it is important to emphasize, that this does not affect the lane keeping. In contrast, the SDLP was the lowest during the use of the IASS. In addition, the simulator setup in this study included a gaming steering wheel, which differs in size and shape from a series production steering wheel. Therefore, the influence on the steering behavior might be tested again with a suitable steering wheel. If necessary, the high-paced shoulder sequence should be slowed down.

The improvement of lane keeping through the IASS was statistically significant for SDLP and SDSA but not for MDFL. The reason for this might be the large variance of MDFL between subjects. The development of fatigue and its consequences shows strong inter-individual differences (Nilsson et al., 1997). This could be particularly evident in the case of MDFL, since this parameter only increases in advanced stages of fatigue, when the vehicle has left the lane.

7.4.3 Vital parameters

Based on the literature, all three captured vital parameters are influenced by passive driver fatigue, physical activity as well as task complexity. Therefore, changes in these parameters cannot directly be associated with one of the three listed factors. As a result, in interpreting the three parameters, the context in which alterations occur, has to be considered as well.

At the beginning of this chapter, the vital parameters shall be interpreted in the context of passive driver fatigue. For this purpose, the consideration of the parameters over the course of the study gives the best information. Heart rate increased significantly over time in all three conditions. Descriptively, this was also the case for the skin conductance level in the passive and the control condition, although the increase was only significant in the latter. As subjective passive driver fatigue increased in the course of the study, these findings are somewhat surprising as both parameters are expected to decrease with increasing fatigue.

One explanation could be that monotony led to increasing frustration during the course of the study. For example London et al. (1972) found increased arousal due to boredom which resulted in increased galvanic skin response and heart rate, when comparing boring with more interesting tasks. Van Hooft &

van Hooff (2018) describe that boredom can generally cause both low and high arousal, depending on the situational context. Their studies indicate that when task autonomy is low, boredom related to more frustration including negative high-arousal reactions, than when task autonomy is high. On the one hand, the task autonomy in this study could be considered low because the subjects had to follow a fixed schedule. On the other hand, they were free to leave at any moment, participated voluntarily and probably saw a higher purpose in the study (e.g. contribution to science). To the best of the author‘s knowledge no studies exist in the driving context, that directly investigated frustration due to boredom that included the analysis of vital parameters. Accordingly, this explanation should be considered vague and would definitely need further investigation.

Another explanation for the increasing heart rate and skin conductance might be changing of the room temperature. The study took place in summer and no air-conditioned room was available. Therefore, there was occasionally a noticeable increase in room temperature during the course of the study. The influence of ambient temperature on heart rate was for example investigated by Yamamoto et al. (2007). Increasing the temperature from 21 to 35 degrees for 30 minutes significantly increased the heart rate from 67.4 to 87.6 bpm while the subjects were seated in a chair. Additional studies showing increased heart rate due to heat exposure can for example be found in Carrillo et al. (2016) as well as in Ketelhut & Ketelhut (2019). As the SCL is influenced by the hydration of the corneum, this parameter also increases with elevated ambient temperature in the normal room temperature range (M. E. Dawson et al., 2007). To get a better estimation of the influence of room temperature in this study, the mean SCL curves of the morning and afternoon session were plotted again separately (see Appendix F). Higher SCL values occurred in fact during the warmer afternoon session. However, if one assumes that sweating caused the increased SCL, it is surprising that the values sharply dropped after the use of the IASS. The sharp drop down occurred in both the morning and the afternoon session (see Appendix F, Figure 41). This is contradictory, as the IASS represents a physical activity. It is therefore to be expected that the IASS increases sweating and consequently elevates the SCL.

Another influencing factor on SCL is time on day, with increasing values throughout the day (Hot et al., 1999). This could also be an explanation for higher values in the afternoon compared to the morning session. A contradictory argument for this explanation is that the values in the first three minutes of both sessions are identical and only start to differ afterwards. If time of day was the influence, the values should actually differ from the beginning.

In summary, it is not entirely clear why both SCL and HR increased over time. In future studies, temperature should be accurately documented as it is the most likely confounding factor. However, from the author's point of view, the analysis and interpretation of the vital data concerning mental workload and physical activity is nevertheless meaningful. After all, the most likely influence of heat and time on day should affect all conditions equally because they were randomized.

During time interval *Int.*, heart rate was significantly elevated through the IASS, in comparison with both the massage seating system and the control condition. Within the active condition, both the heart rate and the skin conductance were significantly higher during the use of the IASS in comparison to before and after. As both higher task complexity and physical activity increase heart rate, it remains unclear, which of the two is the main cause of the findings.

A discussion that mental effort generally increases heart rate can be found in Brookhuis & de Waard (2010). A discussion of these effects in the driving context was made by Coughlin et al. (2011). The authors demonstrated that both SCL and HR increase with different levels of cognitive demand of secondary tasks while driving. This was for example demonstrated for an auditory-prompt verbal response n-back task (Mehler et al., 2009), scored working memory digit recall task (Mehler et al., 2011), an auditory delayed digit recall task (Reimer & Mehler, 2011) and a verbal working memory n-back side task (Lenneman & Backs, 2009). More ordinary tasks were investigated by Collet et al. (2009). The authors found a significantly increased heart rate and lower skin resistance[6] through listening to radio, conversation with passenger and phone conversation.

Within the active condition, the mean heart rate increased from 68.7 bpm to 74.0 bpm from before (*Prae*) to during the use of the IASS (*Int.*). This equals 5.3 bpm. The increase in HR due to additional cognitive tasks while driving is well up to 9 bpm, according to the literature previously listed in this chapter, (e.g. Mehler et al., 2009, 2011; Reimer & Mehler, 2011). The study by Hiemstra-van Mastrigt et al. (2015) gives an indication how much the physical effort while using an ADSS can influence the heart rate. The authors investigated a ball-balance game in a passenger car seat and found an increased heart rate by 15.2 bpm. However, the psychological arousal through the game might have affected the heart rate as well. In conclusion, it is difficult to determine to what extent task complexity or physical activity are responsible for the increase in heart rate.

The massage seating system did not significantly influence any of the vital parameters. Descriptively, the heart rate tended to decrease during its use. The heart function is controlled by the sympathetic and the parasympathetic system. While the first promotes arousal, the second is responsible for maintaining bodily functions and resting, what is associated with a decreasing heart rate (Solovey et al., 2014). Thus, a tendency towards relaxing rather than activating effects of the MS, can be assumed.

Heart rate variability, showed no systematic changes over time or due to the interventions, in contrast to HR and SCL. Bier et al. (2018) state that a sampling frequency of 500 Hz or higher should be selected to reliably capture the variability of RR-intervals when PDF is analyzed with HRV. This specification should be transferable for the general recording of HRV, which also includes the analysis of physical activity and mental workload. In this study, a sampling frequency of only 256 Hz was used, which might have negatively affected the resolution of the HRV. Conversely, other authors have found a decreasing HRV through an alertness maintaining secondary task in the driving simulator despite using a

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[6] Which in turn corresponds a higher skin conductance, see Chapter 2.4.4.

sampling frequency of only 250 Hz (Oron-Gilad et al., 2008). Therefore, it is not entirely clear why HRV was not suitable in this study.

7.4.4 Eye tracking parameters – passive driver fatigue

The increasing PDF over time that was observed with KSS and lane keeping ability, was also partially evident in the eye tracking parameters. The eyelid distance decreased over time in all three conditions, even though the alteration was only significant in the passive condition. During the use of the IASS, eyelid distance was significantly larger compared to the MS or no intervention, indicating that PDF was reduced. However, contrary to the literature, no systematic differences occurred in blink duration and frequency.

One explanation for the lack of effect might be that the change over time in the statistical analysis does not reflect a comparison from before to after the trip. Instead, the largest time difference exists for the comparison between *Prae* and *Post*, which equals approximately 20 minutes. Consequently, there could be two reasons that might explain the absence of effects: 1) Fatigue was already too far elevated in time interval *Prae* or 2) The time difference between *Prae* and *Post* was not long enough to cause systematic effects.

However, from the authors' point of view, this only partially limits the validity of the results. Subjective fatigue and lane keeping ability are of primary interest, as they reflect if the subjects felt better and drove safer. Contrarily, the eye tracking data was only intended to explain these effects on a physiological level. Moreover, other authors found mixed results when investigating PDF with eye tracking as well (Larue et al., 2011).

7.4.5 User experience and Emotional perception

Compared to the MS the IASS was rated significantly better on the following items: wellbeing, activation, fun and usefulness. The IASS was also perceived as significantly more exhausting, which met expectations since the users only had to execute active movements when using this seating system. The more important finding is that also the IASS was experienced as very low exhausting. This is in line with the goals of the system, which is intended to be a moderate movement program and not a fitness workout.

The more activating effect of the IASS was also reflected in the emotional perception of the seats. In comparison to the active condition, the emotion ‘calm neutral’ was mentioned three times as often for the seat after the passive condition and four times as often after the control condition. In contrast, the emotion ‘excited pleasant’ was only experienced in the active condition.

However, the IASS and MS were rated as being equally relaxing on the Likert scale. Usually, one of the main goals of massage seating systems is to relax the passengers (Franz, Zenk, et al., 2011). The question is whether massage systems are appropriate in situations with increased risk of PDF. The calming effect might further increase passive driver fatigue under such circumstances, which paradoxically might eliminate relaxation. This aspect could be investigated in more detail in the future. This could also include examining the effect of different inflation parameters of the massage e.g. intensity and frequency.

In summary, among the three seats, the one with the IASS elicited the most pleasant emotions. The subjects were asked for the emotion that a perfect car seat should evoke. Among the participants, 67 % stated emotion (E) ‘average pleasant’ in the preliminary questionnaire and 55 % in the final questionnaire (Q2). This emotion was also most frequently chosen as the preferred one with 71 % in the study of Kamp (2012). The emotion was induced three times more often by the IASS compared to the MS and no seating system. This is one of the reasons, why the IASS compared to the MS or no seating system, was 2.5 times more likely to meet the emotional expectation of a seat.

The subjects stated they would use both seating systems equally often, but there was a much higher purchase propensity for the IASS.

7.4.6 Sitting comfort and discomfort

Only the IASS improved comfort significantly in comparison to no seating system. The IASS also significantly reduced discomfort in comparison to both the MS and no seating system. However, all comparisons only showed small effect sizes. This might be primarily caused by the short duration of the conditions, as at least discomfort increases with time (e.g. Falou et al., 2003; Mansfield et al., 2015; Smith et al., 2015). As subjects were allowed to stand up during the breaks between conditions, they only sat for 40 minutes straight. Additionally, a high-end seat was used in the study. Such seats already offer high comfort and elicit low levels of discomfort without seating systems (Hiemstra-van Mastrigt et al., 2015; van Veen et al., 2015; Varela et al., 2019). Another factor on sitting discomfort that was neglected in this study is the occupant's exposure to vibration (Mansfield et al., 2015).

Despite first promising results of the IASS, future studies with longer durations that include vibration exposure might provide more in-depth information of the influence on comfort and discomfort.

7.4.7 Workload

The DALI questionnaire revealed that the majority of subjects perceived a low overall task difficulty, interference and situational stress in all three conditions.

The occurrence of such a low situational stress is somewhat surprising. Especially in the passive and control condition where a significant increase in subjective fatigue and deterioration of lane keeping ability was measured. One reason for the low ratings could be that fatigue is only listed as one exemplary aspect among several of situational stress in the questionnaire. Therefore, subjects might have used averaging between all listed exemplary factors. As a consequence of the low ratings, no significant differences between conditions were measured regarding situational stress.

The IASS significantly increased the overall task difficulty in comparison to the control condition, whereas this was not the case for the MS. Both the IASS and MS resulted in significantly increased interference compared to the control condition, with a significantly higher level of interference for the IASS compared to the MS. However, all significant comparisons showed a small effect size.

A possible explanation for the missing or small differences between conditions in general is given by Cegarra & Chevalier (2008). The authors state that the NASA-TLX is a static measurement that does not allow capturing the dynamics of the load and is therefore not sensitive to within-task changes. It is likely that this equally applies to the DALI questionnaire, as it is based on the NASA-TLX. Of the

40 minutes of each condition, only around 7 minutes actually differed (introduction and program). If the subjects assessed the whole ride over 40 minutes, this might have led to relatively small differences in ratings between conditions.

Nevertheless, the study showed that the IASS increased task difficulty and interference while improving driving performance. This generally supports the hypothesis that despite the increase of task complexity, a secondary task can simultaneously reduce monotony, leading to a better performance. A better performance in turn is an indication for lower overall workload.

Whether questionnaires indicate a high or low overall workload in such situations depends strongly on the weighting of the questions that reflect monotony or task complexity. The DALI for example mainly includes questions that reflect task difficulty. Based on the model from Chapter 2.2.2, it should be discussed, whether monotony should be taken more into account in such questionnaires in the future.

Additionally to the subjective evaluation, pupil size was recorded to give objective information about task complexity. Pupil diameter is expected to increase with task complexity. Descriptively, the use of the MS resulted in a larger pupil diameter, whereas this was not the case for the IASS. Even though the increase did not become significant, the tendency does not meet the expectation. Firstly, according to the DALI the highest task difficulty and interference was experienced during the use of the IASS. Secondly, as described in Chapter 7.2.2 an increased pupil diameter was found for additional mental tasks while driving. As an additional motor task, the IASS involves cognitive components as well. The MS, on the other hand only provides additional stimuli.

In conclusion, the subjective assessment of workload only showed small or no effects. Therefore, it can only make a limited contribution to the validation of the model from Chater 2.2.3.3. Fundamental research, with the explicit objective of verifying the theory, is necessary to provide a clearer picture in the future.

7.4.8 Driving simulator

In line with 85 % of the literature listed by Bier et al. (2018) that examined PDF, this study took place in the driving simulator. Only 13 % of such investigations used real driving and 2 % a combination of both. For simplicity, the study used a rather simple driving task and only lane keeping ability as a measure for driving performance. This seems appropriate as the IASS was evaluated in an early development stage, and most crashes caused by PDF happen on monotonous highway roads, with cars leaving the road (see Chapter 2). Nevertheless, this chapter gives a brief discussion of the validity of simulator studies.

An important advantage of simulator studies is the controllability, reproducibility and standardization in terms of traffic and weather conditions (de Winter et al., 2012). This was a crucial factor in this study, which was conducted at day to increase the likelihood that PDF and not sleepiness was measured. The study took place in an area with a rather high traffic volume (Stuttgart, Germany). On the one hand high traffic density can reduce monotony, but it also varies greatly between days. Standardization of lighting conditions was also important, because eye tracking was recorded, a measure that is very sensitive to varying lighting conditions. Another advantage of driving simulators is the fact, that data can be collected easily and reliably, which is especially the case for the lateral position of the vehicle (de Winter et al., 2012). It should also be considered that the IASS was evaluated for the first time and its effects were unknown. Therefore, the highest priority was to prevent participants and other road users from physical danger. However, the absence of danger is also critically discussed in the literature. Since errors in the simulation have no real consequences, participants might show more risky driving behaviors (Käppler, 2008).

Despite this disadvantage, literature suggests a sufficient validity to use simulators for the purpose of this study. In general, a division is made between absolute and relative validity of simulators (Wynne et al., 2019). In the first case, the captured values in the simulator and real world match in absolute terms. In the second, the parameters show the same effects but with different magnitude.

Absolute validity as a result of weariness was found by Davenne et al. (2012) for lane keeping ability and subjective sleepiness. However, usually relative validity is reported as a result of weariness. This was for example found for the effects of sleepiness and fatigue on subjective weariness, blink duration, standard deviation of lane position, number of line crossings and reaction time (Hallvig et al., 2013; Philip et al., 2005). Thereby, the effects of weariness were higher in the simulator. Relative validity was also captured for the effects of a secondary task in form of a phone task on lane keeping and speed control (Reed & Green, 1999). The previous findings are supported by a review with 44 studies from Wynne et al. (2019). The authors conclude that lane keeping generally shows strong relative validity.

Relative validity was also found for ratings of workload with NASA-TLX (Lobjois et al., 2021), with higher ratings in the simulator. Relative validity was also captured for vital parameters with similar values for oxygen consumption and mean ventilation but a higher heart rate in real driving (Johnson et al., 2011). Li et al. (2013) even identified absolute validity for heart rate.

It is however assumed, that the validity of a simulator dependents on its fidelity, which is not limited to the hardware. Fidelity of a simulator includes many more aspect, such as physical, perceptual, behavioral, functional, psychological and visual fidelity just to name a few (de Winter et al., 2007; Goode et al., 2013). Consequently, determining the validity of a simulator is extremely complex. Nevertheless, it can be assumed that the simulator used in this study can be at least classified as medium-fidelity simulator, since it included a realistic presentation of the road, a motion base platform as well as the high-quality controls.

Before the simulator ride, the subjects completed a test session lasting up to five minutes in this study. Ronen & Yair (2013) observed that it takes some time for novices until automation of simulator driving occurs. As a result, they found an exponential improvement of different driving parameters at the beginning of the ride, which stabilized afterwards. Contrarily, in this study a linear decrease of driving quality was already observed from the beginning. This is an indicator that the subjects got used to the simulator in the training sessions.

In conclusion, the use of a driving simulator can be considered suitable for a first study. The relative validity is a good basis for a valid estimation of the effects of the seating systems.

Nonetheless, the effects of the IASS should be tested in more complex simulator or real world driving studies in the future. In these studies, subjects could be given the opportunity to choose their own speed. De Waard et al. (2001) found that subjects slowed down when performing an additional task in order to compensate for the increase of task complexity. The same behavior was detected by B.-S. Liu & Lee (2006) for an additional mathematical task via cellular phone. Based on the model in Chapter 2.2.3.3, it is expected that users could maximize the beneficial effects of the IASS in this way. By reducing speed, they can compensate for the increased task complexity of the additional task, while still benefitting from the reduced monotony, leading to the lowest possible overall workload.

Additionally, future studies should also measure other aspects of driving quality, such as reaction times. This could provide a more comprehensive understanding of the effects of the IASS.

In this study, the majority of subjects felt very comfortable performing the motor task while driving in the simulator. Future research should evaluate whether the use of the IASS also feels comfortable in real world driving. This is important because the IASS will only achieve a high level of user acceptance and thus efficacy if it feels safe to use.

7.4.9 Interactive seating prototype

The limitations of Study I (see Chapter 5.8) included, that the optimal sensor locations for the interactive seating prototype were determined in the standing vehicle. Therefore, the sensor locations were determined under exclusion of possible confounding factors of driving, such as acceleration forces. Nevertheless, the prototype worked very reliable in this study. Even though a simulator ride cannot replace real driving, the author assumes that the system would also work robust in the latter. Nonetheless, the system should be tested under real driving in the future. Only in this way, the full functionality can be assured. This, however, would go beyond of the scope of this thesis.

7.5 Limitations

In this study, the IASS was introduced to the subjects for the first time. The novelty of the system may have developed a curiosity that influenced both monotony and the user experience rating. The sample consisted exclusively of employees of Mercedes-Benz AG, which might have further amplified this effect. For this reason, studies with subjects outside the automotive sector should be carried out in the future. In addition, it should be examined whether the alerting effect of the IASS still exists after repeated use.

7.6 Conclusion

This study investigated the effect of a secondary motor task on passive driver fatigue induced by an interactive seating system. The IASS was compared to a control condition and a massage seating system, which induced tactile stimuli to reduce monotony. Only the IASS was able to reduce PDF, reflected by less subjective fatigue, improved lane keeping and increased eyelid distance. The vital parameters support these findings, even though it remains open, to what extent their activation is induced by a reduction of PDF or enhancement of physical activity and task complexity. In contrast, the MS demonstrated for none of the listed parameters a beneficial effect compared to the control condition.

The IASS was also preferred over the MS in terms of user experience and emotional perception. Additionally, comfort and discomfort benefited more from the IASS compared to the MS.

No systematic patterns were found in both eye blinking parameters and the heart rate variability in any of the conditions. Why the three parameters were not able to capture PDF in this study remains unclear.

8. Study III – Physical activity in stationary vehicle

This chapter was published in a largely similar form in Lampe & Deml (2022a).

8.1 Introduction and Abstract

Chapter three described health-risks through prolonged sitting in the vehicle. With the aim of reducing these risks, the following study investigated the effects of the IASS on muscular and cardiorespiratory activity. For this purpose, the IASS was compared to the state-of-the-art massage seating system from Study II in a laboratory study in the vehicle including 30 male subjects. The first objective was to compare the systems regarding their influence on heart rate, which reflects general physical activity. As described in Chapter 3.1 increased physical activity is associated with a reduction of metabolic and cardiovascular risks of sitting. The second objective was to determine if the systems activate target muscles of exercises that potentially reduce musculoskeletal pain in vehicles. As described in Chapter 3.2 this includes activation of trunk muscles and the m. gluteus maximus to reduce lower back pain, and the m. trapezius pars transversa and m. trapezius pars ascendens to reduce neck and upper back pain. Within this context, it was also investigated, whether the lumbar and the shoulder sequences within the program of the systems (described in Chapter 4.2.2) activate different muscles. The third objective was to compare the systems regarding their influence on sitting comfort and discomfort. To the author's knowledge, this is the first study to directly compare the physical effects of an ADSS with a PDSS in an automobile.

Heart rate was captured with electrocardiography (ECG) and activity of six muscles with electromyography (EMG). Comfort and discomfort were captured with questionnaires.

Results: Heart rate was significantly elevated trough the use of the IASS, the MS in contrast showed a tendency to lower the heart rate. When using the MS, the muscle activity was only increased in the lower back, whereas activity was increased in all six captured muscles when using the IASS. Significantly less discomfort was found for the IASS compared to the MS.

Literature recommends increasing physical activity for reducing health risks of static sitting. This was achieved with active movements through the IASS, whereas passive movements through the MS showed limited success.

8.2 Material and Methods

8.2.1 Setup

Figure 51 shows the setup of the study which was conducted in the laboratory. In line with the EMG measurements in Hiemstra-van Mastrigt et al. (2015), the study was conducted in a stationary vehicle. This decision was made because influencing factors such as vibrations from the vehicle can affect the EMG signals. Since this was the first time that the IASS was studied using electromyographic measurements, priority was given to avoid possible confounding effects. This means, the participants sat in a real vehicle, but they did not drive during the study.

Figure 51: *Illustration of the measurement setup. The right screen showed a video that was played during the ride (Dash Cam Tours, 2021), the left screen showed the user interface. Due to a missing copyright permission, the right screen was grayed out for this image.*

A Mercedes-Benz GLE (V167 series) was equipped with the interactive seating system on the front passenger seat. Two screens were positioned in front of the car (LG 65LA9659 – ZA; screen diagonal 65 inch; resolution 3840 x 2160). During the use of the IASS, the left screen showed a user interface. The user interface (see Figure 52) was slightly changed from the one used in Study II (described in Chapter 7.2.1). In addition to the previous version, the user could collect points by interacting correctly with the IASS. The additional score bar at the bottom of the user interface visualized the current score. The right screen played a video showing a ride on the highway (Dash Cam Tours, 2021).

ECG and EMG were captured with the following device: Becker VARIOPORT-B (Becker Meditec, Karlsruhe, Germany).

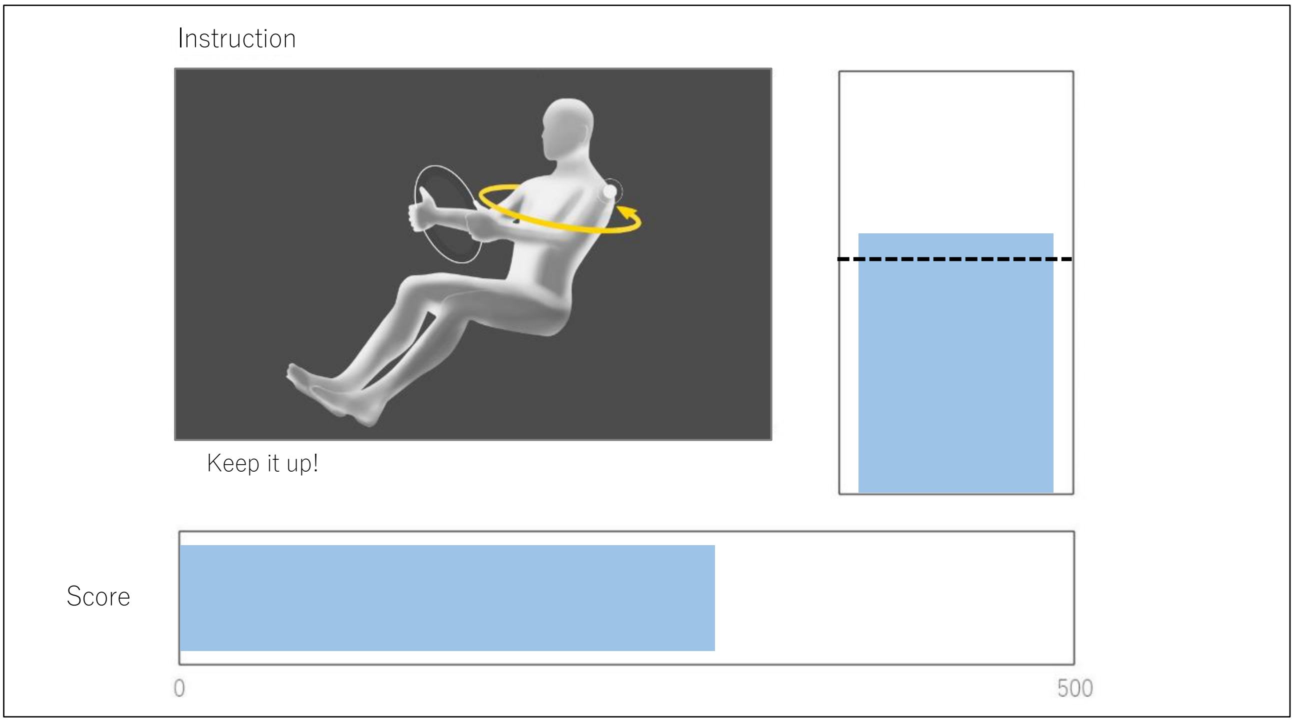

Figure 52: *User interface of the interactive seating system. On the left side, illustrations of the target movements are shown. On the right side, a bar plot shows the current pressure value of the target air bladder and a user-specific pressure threshold (dotted line) that was determined beforehand with a calibration measurement (see Chapter 6). The top end of the bar should now be moved above the line by pressing against the currently inflated air bladder. The user can collect points through a successful interaction. The scorebar at the bottom visualizes the current score.*

8.2.2 Measures

Electrocardiography

ECG measurements were captured to calculate the heart rate. As in Study II, the electrodes were attached following the MC5 lead (Hamm & Willems, 2014): reference electrode on the xiphoid process of the sternum, positive electrode on the manubrium of the sternum, negative electrode in the area of the fifth intercostal space on the anterior axillary line.

Electromyography

According to the literature presented in Chapter 3.2 strengthening of trunk muscles is recommended as a measure against CLBP. Therefore, muscle activity of the m. longissimus (M. Long), m. rectus abdominis (M. RA) and m. obliquus internus abdominis (M. OIA) was measured. The muscles are located superficial, thus they can be measured well with surface electrodes. In addition, the m. gluteus maximus (M. GM) was measured as strengthening of this muscle further increases the efficacy of core-exercises against CLBP (Jeong et al., 2015). Finally, the M. trapezius pars ascendens (M. TPA) and M. trapezius pars transversa (M. TPT) were measured, as strengthening of these muscles is suggested as a countermeasure against the upper crossed syndrome (see Chapter 3.2).

Only the activity of the left-sided muscles from the subject's point of view was measured. The electrodes for electromyography (EMG) were positioned according to SENIAM (2020) for the following muscles: M. GM, M. Long, M. TPA and M. TPT. As no information was provided for the abdominal muscles by SENIAM (2020), the M. RA was positioned according to Huebner et al. (2015) and Ng et al. (2002) and the M. OIA following Boccia & Rainoldi (2014). Exact information about the positioning of the electrodes is given in Appendix G.

Before attaching the EMG electrodes, the skin was prepared as recommended by Hermens et al. (2000) and Pfeifer et al. (2003): (1) shaving (2) abrasion of the skin with sandpaper (3) cleaning with alcohol. For reducing motion artifacts, both the ECG and EMG electrodes were fixed to the skin with adhesive tape. Ag/AgCl electrodes with decentralized pushbuttons were used (Ambu Neuroline 72000-S/25).

Sitting comfort and discomfort

Similar to Study II, the assessment of comfort and discomfort was made with a German translation of an adapted version the Chair evaluation checklist (Helander & Zhang, 1997). The following statements for discomfort and comfort had to be rated with items ranging from (1) ‘not at all’ to (9) ‘extremely’:

Discomfort: (1) ‘I have sore muscles’; (2) ‘I have heavy legs’; (3) ‘I feel uneven pressure from seat pan or seat back’; (4) ‘I feel stiff’; (5) ‘I feel restless’; (6) ‘I feel tired’

Comfort: (1) ‘I feel relaxed’; (2) ‘I feel refreshed’; (3) ‘The seat feels soft’; (4) ‘The seat is spacious’; (5) ‘I like the chair’

The initial version of the questionnaire also includes the statement ‘The chair looks nice’ for comfort. As the seat looked the same in both conditions, this statement was excluded from the questionnaire.

8.2.3 Experimental Design

8.2.3.1 Conditions

The conditions were the same as in Study II; however this study did not include a control condition. The first condition was the *active condition* (AC), where the IASS was used as intervention. In the *passive condition* (PC)*,* the air bladders of the IASS were used as a massage seating system (MS). During the inflation of the air bladders in the PC, subjects were instructed to let themselves being mobilized with no interaction.

8.2.3.2 Procedure

Figure 53 illustrates the procedure of the study. Every subject completed both conditions in succession (repeated measures design). The order of conditions was randomized, such that these were equally distributed. In the beginning, the subjects sat into the vehicle and adjusted the front passenger seat individually until they felt comfortable comparable with previous studies (e.g. Falou et al., 2003). The next step was a sensor calibration procedure for the IASS, which is analogous to the passive condition (see also Chapter 6). Afterwards the subjects completed both conditions. In the beginning of each condition, the subjects completed a pre-questionnaire. Afterwards the video with the ride on the highway was started.

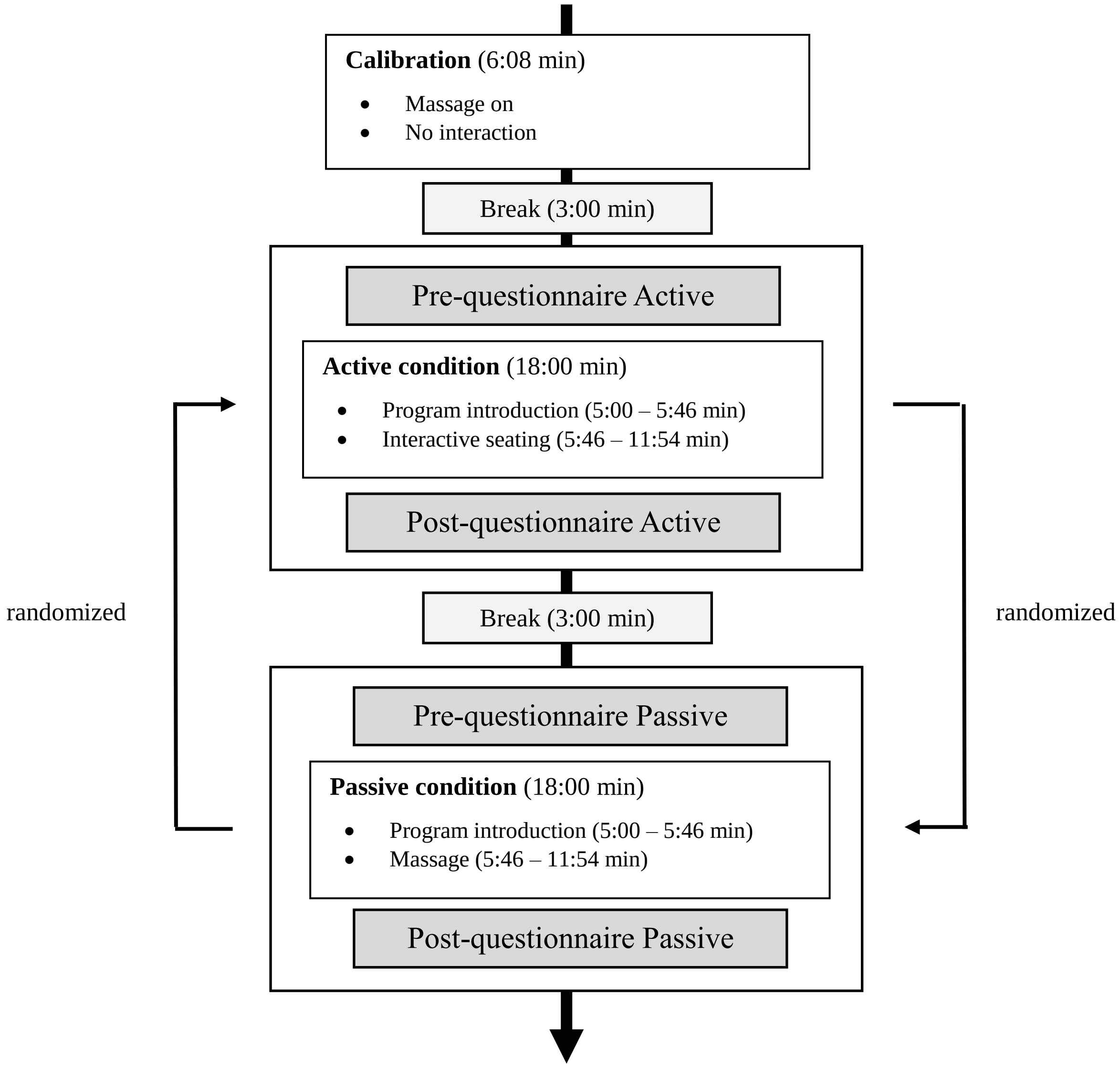

Figure 53: *Illustration of the study procedure.*

After sitting in the vehicle for 5:00 min, an introduction with a length of 0:46 min was played via the audio speakers. In the AC, the introduction explained the movement task. In the PC, the subjects were asked not to interact with the system. The introduction was followed by the intervention i.e. the MS or IASS at 5:46 min. Each intervention lasted 6:08 min until 11:54 min. After the intervention, the subjects sat for another 5:00 min in the vehicle and completed the post-questionnaire.

8.2.3.3 Subjects

The subjects were employees of Mercedes-Benz AG, but they were not familiar with the project or the objectives of the study. Thirty-one male subjects participated in the study. One subject had to be excluded from the sample due to a lack of German language skills. Consequently, thirty valid data sets were included in the analysis. The mean age was 39.5 years (± 10.9 years, range from 26 to 62 years), mean body mass 80.9 kg (± 10.5 kg, range from 65.7 to 115 years), and mean height 177.9 centimeters (± 7.0 centimeters, range from 167.0 to 187.5 centimeters). Only male subjects were included because internal guidelines required that EMG electrodes have to be attached only by same-sex investigators to preserve the subjects' intimacy. Unfortunately, no female investigators were available at the time of the study.

8.2.4 Data analysis

8.2.4.1 Signal processing of ECG and EMG data

ECG and EMG were captured with a sampling frequency of 128 Hz. The raw signals were processed in Mathworks® Matlab® R2018b. The ECG-signal was similarly processed to Study II (see Chapter 7.2.2). The EMG-Signal was filtered with an analog bandpass filter with cut-off frequencies of 19 Hz and 400 Hz which is in line with the recommendations of De Luca et al. (2010). Subtraction method (Hof, 2009) was used to remove ECG artifacts from the EMG signals. After the procedure, the signal was again digitally highpass filtered with a cut-off frequency of 20 Hz. Visual inspection of each data set showed that none of the datasets was affected by motion artifacts. As the final step, the root-mean-square

(RMS) was calculated comparable with previous studies (Franz et al., 2008; Franz, Zenk, et al., 2011; Kolich et al., 2000; Menotti et al., 2015).

8.2.4.2 Statistical analysis of ECG and EMG data

For the statistical analysis of the heart rate data, three time intervals were defined: *Prae* (00:30 – 05:00 min), *Int.* (05:46 – 11:54 min) and *Post* (12:24 – 16:54 min). The EMG data was divided into four time intervals, because it was of interest to investigate if the muscle activity differs between the lumbar and the shoulder sequences: *Prae* (00:30 – 05:00 min), *Lumbar* (5:46 – 7:18, 8:32 – 10:47 min), *Shoulder* (7:18 – 8:32, 10:47 – 11:54 min) and *Post* (12:24 – 16:54 min).

Heart rate was analyzed with a univariate 2 x 3 two-way repeated measures ANOVA with the independent variables conditions (AC/PC) and time interval (Prae/Int./Post). Muscle activity was analyzed with a univariate 2 x 4 two-way repeated measures ANOVA for each muscle with the independent variables conditions (AC/PC) and time interval (Prae/Lumbar/Shoulder/Post).

Not all data was normally distributed. However, since ANOVAs are considered to be robust against a violation of normal distribution for equal sample sizes, they were considered suitable for this study (Field et al., 2012; Schmider et al., 2010; Wilcox, 2012). Nevertheless, the result of the Shapiro-Wilk test for each dataset is listed in Appendix H. If the assumption of sphericity had been violated, degrees of freedom were corrected using Greenhouse-Geisser for both the heart rate and EMG data. Pairwise comparisons were made using paired t-tests with Bonferroni correction for multiple testing. Effect sizes were calculated with Cohen’s D (Tomczak & Tomczak, 2014). The following classification for effect sizes was applied (J. Cohen, 1992): small ($0.2 \leqslant d < 0.5$), medium ($0.5 \leqslant d < 0.8$) and large effect ($0.8 \leqslant d$).

8.2.4.3 Statistical analysis of comfort- and discomfort questionnaires

The participants rated comfort and discomfort in the pre- and post-questionnaire in both conditions. Changes over time were calculated by subtracting the ratings after each condition from those before. Afterwards the mean was calculated for all five comfort statements to receive overall comfort, and likewise for the six discomfort statements. Negative values represent a decrease of comfort/discomfort over time and vice versa. Statistical analysis was performed with Wilcoxon Signed-ranks tests, effect size was calculated with correlation coefficient r (Tomczak & Tomczak, 2014). The statistical analysis of the ECG and EMG data as well as the questionnaires was performed in IBM® SPSS® Statistics 24. With the exception of effect sizes, these were calculated in Microsoft® Excel® 2013.

8.3 Results

8.3.1 Heart rate

The descriptive analysis of Figure 54 demonstrates, that the heart rate was almost identical in the active and passive condition during *Prae* (00:00 - 05:00 min). After that, during time interval *Int.* (05:46 – 11:54 min), the heart rates in the two conditions showed different patterns. In the active condition, the heart rate increased. In the passive condition in contrast, the heart rate decreased during the massage program. After the intervention, the heart rates in both conditions equalized again. In comparison to the time interval *Prae*, the heart rate was slightly higher in time interval *Post* in both conditions. A table listing the exact mean values and variances of heart rate can be found in Appendix I.

The descriptive observations are well reflected by the statistical analysis. The ANOVA revealed a significant main effect for time interval and condition as well as a significant interaction effect with $p < .001$. Exact results for the ANOVA are listed in Appendix J.

In the AC, the heart rate was significantly higher during *Int.* compared to *Prae* and *Post*, with a large effect size, as shown in Figure 54 and Table 23. Contrary effects were found for the PC. Here, the lowest heart rate was found during the massage program. After the program, the heart rate increased again, leading to a significantly higher heart rate in *Post* compared to *Int.* with a medium effect size. No significant differences were found between *Prae* and *Post* in both conditions.

A significant difference between conditions was only found during the interventions. As shown in Figure 54 and Table 23, the heart rate during the use of the IASS in the AC was significantly higher compared to the MS in the PC with a large effect size.

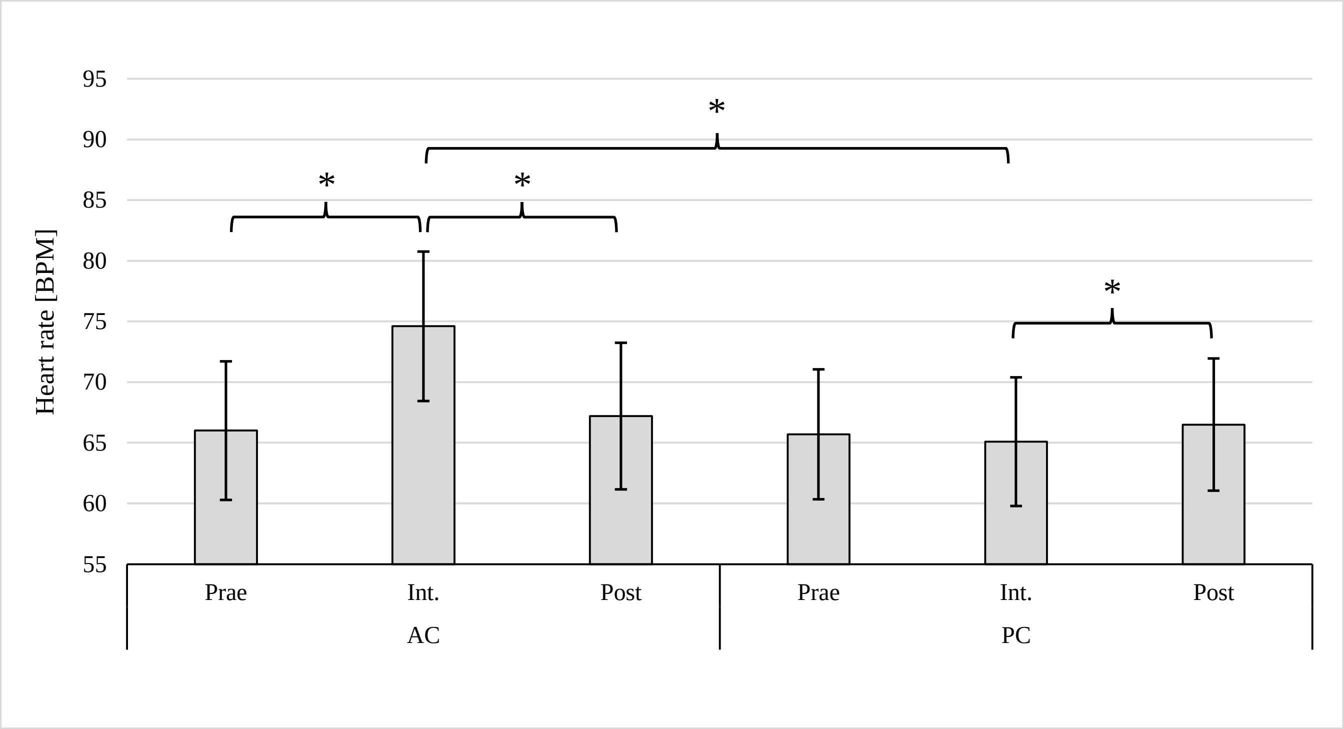

Figure 54: *Mean heart rate in the course of the study. Error bars show the standard deviation. Significant differences (p <.05) are highlighted with *.*

Table 23: *Post hoc comparisons for heart rate. Comparisons with p < .06 are listed and marked with * if p < .05.*

Compare	Mean difference	95% CI		Sig. (| *d* |)
		Lower	Upper	
AC *Prae* vs. AC *Int.*	-8.62	-11.71	-5.53	p < .001 (1.34)
AC *Int.* vs. AC *Post*	7.45	4.82	10.08	p < .001 (1.38)
PC *Int.* vs. PC *Post*	-1.38	-2.29	-0.48	p = .002 (0.72)
AC *Int.* vs. PC *Int.*	9.55	6.96	12.14	p < .001 (1.42)

8.3.2 Electromyographie

The ANOVA revealed a significant main effect for time interval and condition as well as a significant interaction effect with p < .001 for each muscle. Exact results for the ANOVA are listed in Appendix J. The muscle activity within the conditions is illustrated in Fig. 55. Included are all muscles in which at least one post hoc comparison between TIs became significant. All significant post hoc comparisons between both conditions are shown in Fig. 56. The exact values of muscle activity and post-hoc comparisons between conditions including effect sizes can be found in Appendix K. The exact values of the post-hoc comparisons within conditions can be found in Appendix L. In short, the effect-sizes for the post hoc comparisons within as well as between conditions ranged within medium and large.

8.3.2.1 Comparisons within the active condition

M. TPT and M. TPA: The same pattern was found for both muscles. Significantly higher activity during *Shoulder* compared to all other TIs. Activity was also elevated in *Lumbar*, however only the comparison to *Prae* became significant.

M. Long: Activity was significantly higher in *Shoulder* compared to all other TIs.

M. GM: Compared to *Prae* and *Post*, activity was significantly elevated in both *Lumbar* and *Shoulder*. In addition, activity was significantly higher in *Shoulder* compared to *Lumbar*.

M. RA: Significantly higher activity during *Lumbar* compared to all other TIs. Activity was also elevated in *Shoulder*, however, only the comparison to *Post* became significant.

M. OIA: Compared to *Prae* and *Post*, activity was significantly elevated in both *Lumbar* and *Shoulder*. No significant difference between *Lumbar* and *Shoulder*.

8.3.2.2 Comparisons within the passive condition

M. Long: In comparison to *Prae*, activity was significantly higher in both *Lumbar* and *Shoulder*. In addition, activity was significantly higher in *Shoulder* compared to *Lumbar*.

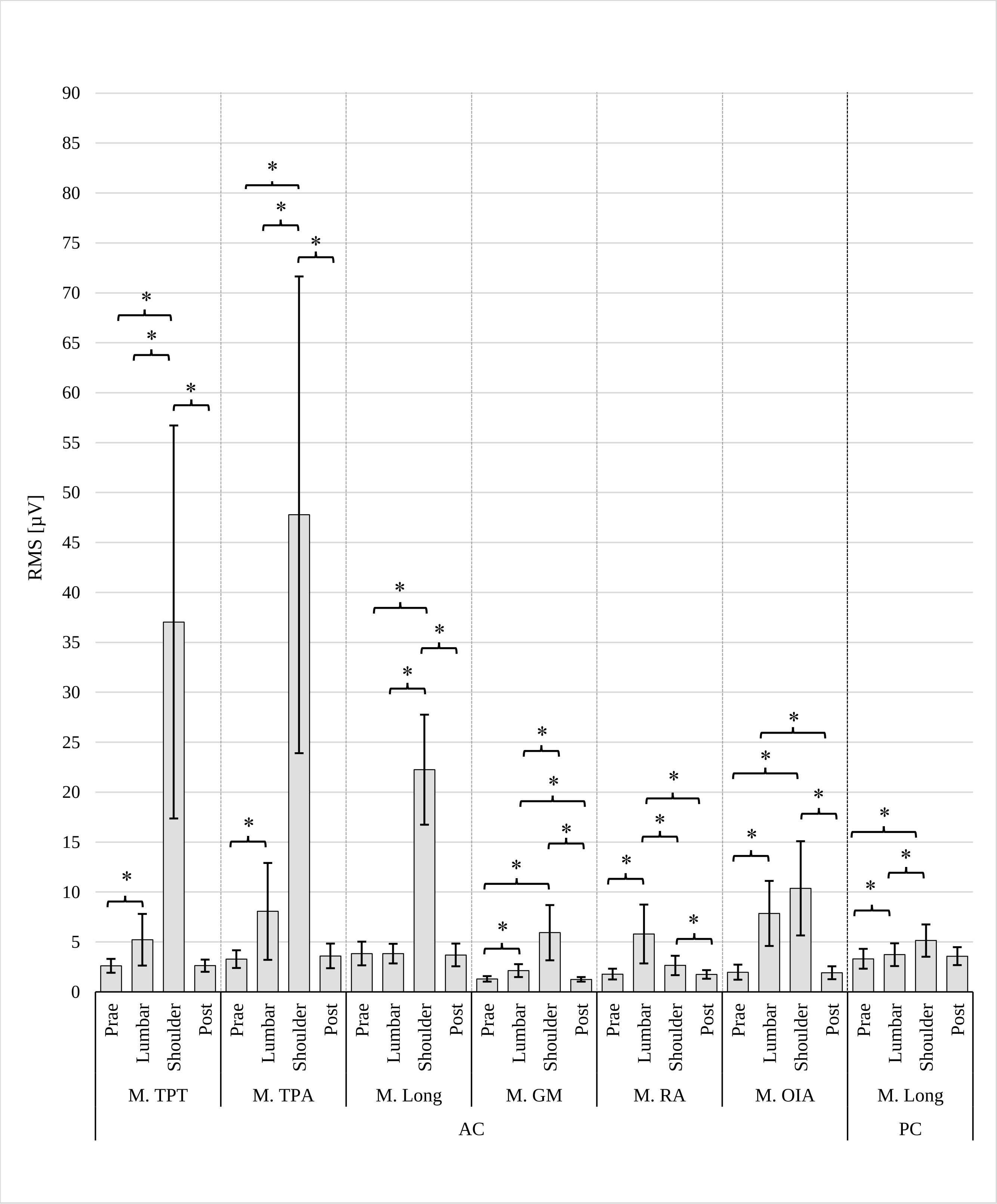

Figure 55: *The figure illustrates the comparisons within conditions. The bar plot shows the mean muscle activity, the error bars indicate the standard deviation. Listed are all muscles that showed a significantly different muscle activity in at least one post hoc comparison between the TIs. In the AC this was the case for all muscles, in the PC only for the M. Long. Significant differences (p <.05) are highlighted with *.*

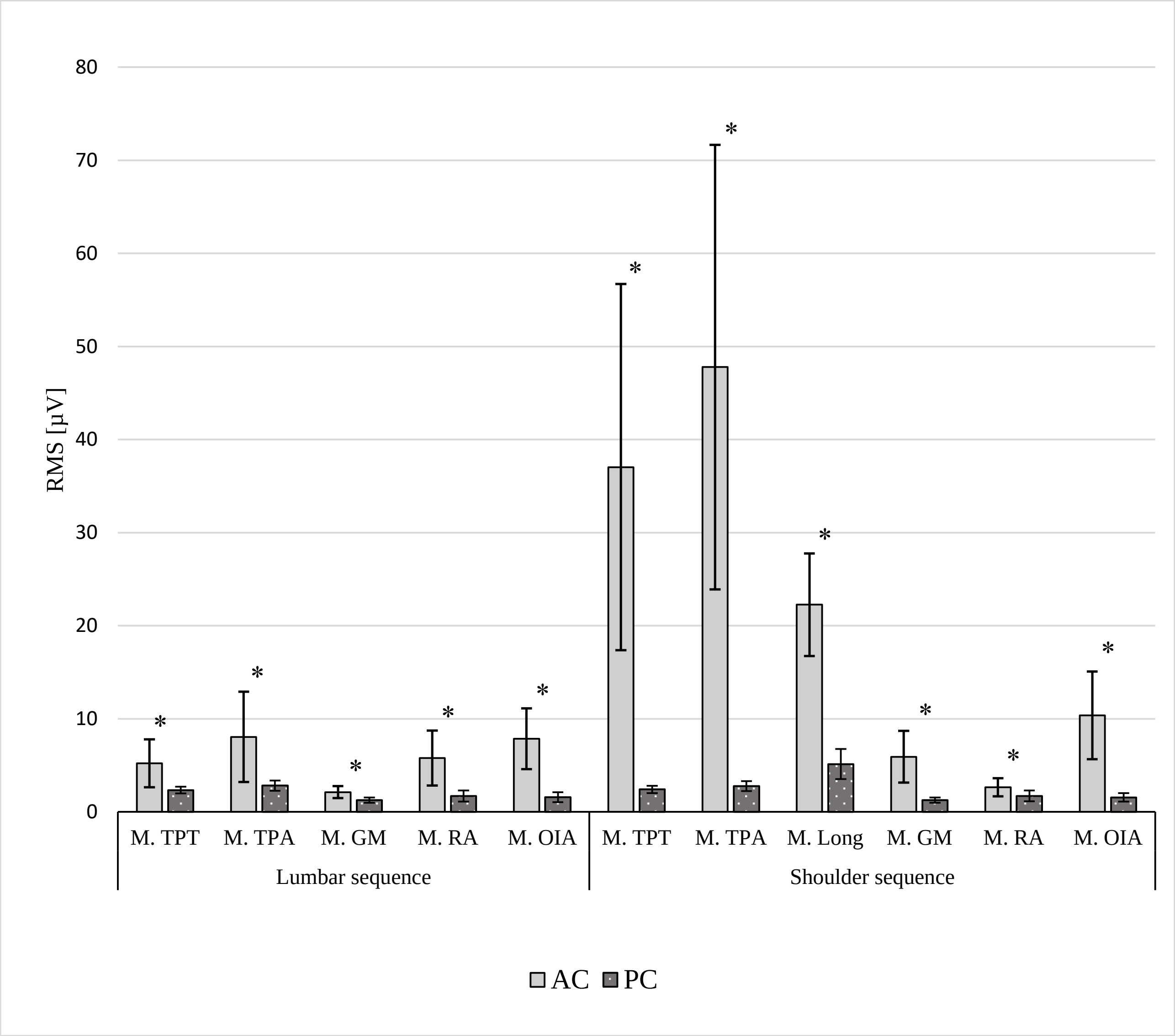

Figure 56: *The figure illustrates the comparisons between conditions. The bar plot shows the mean muscle activity, the error bars indicate the standard deviation. The figure includes all muscles that showed a significantly different activity in the PC compared to the AC during Lumbar and Shoulder. The activity of none of the muscles differed between the PC and the AC in Prae and Post.*

8.3.2.3 Comparisons between conditions

Fig. 56 shows that the activity of all six measured muscles was significantly higher in the AC compared to the PC during *Shoulder*. During *Lumbar* this was the case for all muscles with exception of the M. Long. No significant differences between the AC and the PC were found in *Prae* and *Post*.

8.3.3 Sitting comfort and discomfort

Table 24 shows the results for comfort and discomfort. One subject did not complete the discomfort questionnaire, therefore the analysis of discomfort included data sets from only 29 participants. In general, comfort and discomfort only marginally changed in the course of the study. Comfort slightly increased in both conditions with no significant difference between the conditions. Discomfort increased in the PC but decreased in the AC, and differed significantly between both conditions.

Table 24: *Development of comfort and discomfort in the conditions. Additionally, results of the Wilcoxon tests are listed including effect size.*

Item	Seat. system	Mean ± SD	Min	Max	Median	z	p	| r |
Comfort (N = 30)	IASS	0.05 ± 0.73	-2.0	1.0	0.20	-0.21	.84	0.04
	MS	0.14 ± 0.67	-1.6	1.6	0.20			
Discomfort* (N = 29)	IASS	-0.23 ± 0.72	-2.8	1.5	-0.17	-2.4	.01	0.46
	MS	0.32 ± 0.82	-1.7	3.0	0.17			

8.4 Discussion

The study compared the physiological effects of the IASS with those of a state-of-the-art massage seating system. The first objective was to compare the effect on general physical activity which was measured with heart rate. The second objective was to investigate whether the systems activate target muscles of exercises that potentially reduce musculoskeletal pain in vehicles. For this purpose, muscle activity was measured with electromyography. The third objective was to compare the systems regarding their influence on sitting comfort and discomfort.

The subjects' heart rate was significantly increased through the use of the IASS. The MS on the other hand showed a tendency to decrease the heart rate. Hiemstra-van Mastrigt et al. (2015) studied an ADSS that resulted in a 15.2 bpm increase in heart rate. The ADSS involved a virtual game in which a ball could be balanced by shoulder movements against the seat. This elevation is approximately 8 bpm higher in relation to the effect of the IASS. A comparison of the results of both studies should be made with caution. The sample, the study design and the calculation of the heart rate differ, and Hiemstra-van

Mastrigt et al. (2015) did not calculate effect sizes. Nevertheless, given the large difference of means, it can be assumed that the ball balance game leads to a higher heart rate. However, to what extend the heart rate is further elevated by higher motivation for movements or the arousal of the games remains open.

The IASS significantly activated all six muscles measured. Through the use of the MS, only the M. Long showed an increased activity. However, the activitiy in the M. Long during *Int.* was only increased compared to *Prae* and not to *Post*. Accordingly, conclusions should be drawn with caution. In the authors' view, only a tendency towards increased activity should therefore be interpreted from the data. Increased variability of lower back muscle activity through a PDSS is also reported by Kolich & Taboun (2002). The authors investigated the effects of a pulsating lumbar support with different motion parameters. The authors also found a negative correlation between discomfort and RMS values of EMG. That said, the higher the muscle variability, the lower the discomfort. The reported relationship is in line with the findings in this study, as the IASS in comparison to the MS, led to a significantly higher RMS muscle activity in the lower back and less discomfort.

Activation of the m. trapezius pars transversa and m. trapezius pars ascendens during the use of the IASS was especially found during *Shoulder*. However, both muscles also showed an increased activity during *Lumbar* in comparison to *Prae*. As discussed for the activity of the M. Long during the PC, this is interpreted as a tendency toward increased activity. Nevertheless, these observations did not meet the expectations. The lumbar exercise was expected to specifically activate the trunk muscles (see Chapter 4.2.2). Further visual analysis showed that most subjects showed muscle activity only during the initial filling of the lumbar air bladders after the shoulder sequence. Thus, the activity in these subjects can be explained by the change from the shoulder to the lumbar sequence. On the other hand, in another nine subjects, systematic muscle activity was visible during the entire opening of the lumbar air bladders. The first explanation for this finding is that the exercise was new to the subjects. Thus, the subjects could still have been in a motor learning process during the study and thus activated unnecessary muscles. Another explanation might be, that the subjects received the instruction, to sit in an upright position throughout the exercise (see Chapter 4.2.2). To maintain contact with the backrest, subjects might have actively pulled back both shoulders. In the future, it would be interesting to study both explanations in more detail. This includes the research question, whether the activation patterns of the muscles change over repeated use of the IASS.

In the literature a distinction is made between local and global trunk muscles (Bergmark, 1989). The m. transversus abdominis belongs to the category of local abdominal muscles. Some literature assumes, that this muscle plays a special role in active trunk stability. The reason for this is, that the muscle is pre-activated before body movements in healthy subjects, whereas this is not the case in low back pain patients (Hodges & Richardson, 1997, 1999). Additionally, the muscle was found to be atrophied and more asymmetric in patients with low back pain whereas this was not the case for other trunk muscles.

On the other hand, numerous studies conclude that hip exercises that involve local and global muscles are as good or even superior to an isolated activation of local muscles (França et al., 2010; Liddle et al., 2004; Unsgaard-Tøndel et al., 2010). Accordingly, the specific role of the m. transversus abdominis is under discussion. In this study, the muscle's activity was not measured because it is a deep muscle that is difficult to assess (Retchford et al., 2013). The invasive measurement of muscle activity with needle electrodes did not appear to be appropriate in this study. If the importance of the m. transversus abdominis is confirmed in the future, studies could follow to further investigate its activity.

With the exception of the M. RA, the shoulder sequence produced higher muscle activity compared to the lumbar sequence. From this perspective, the shoulder sequence can be considered more effective. However, after the study, subjects frequently commented that the IASS could be further improved by increasing the number of sequences. This would increase variety and thus motivation. For this reason alone, the program should not be limited to the shoulder sequence.

In future studies, it would also be interesting to examine whether the acute dynamic muscle activity induced by the IASS reduces muscular fatigue caused by prolonged sitting. As described in Chapter 3.2, dynamic muscle activity can promote blood flow and thus may counteract muscle fatigue. The best method of measuring such longer-term effects on the musculature has to be discussed. In general, muscle fatigue is investigated with a frequency analysis of the EMG. In experiments it was shown, the signal amplitude increases and the median frequency decreases with elevated fatigue (Hostens & Ramon, 2005; Kankaanpää et al., 1998). However, this method was used with limited success in driving studies (Falou et al., 2003; Hostens & Ramon, 2005). One explanation might be, that such measurements are normally taken under standardized conditions, when the subject is fixed in a particularly body position and performs a voluntary isometric contraction against resistance (e.g. Kankaanpää et al., 1998). An alternative measurement method might be the measurement of muscle stiffness in the lower back, which is generally expected to increase with prolonged static sitting (Kett et al., 2021; Kett & Sichting, 2020).

8.5 Limitations

The findings of this study are limited to acute effects. The literature suggests that such acute effects can lead to positive long-term effects. However, for certainty, longitudinal studies would have to be conducted first. Only in this way, it can be ensured that the use of a system such as the IASS in everyday life leads to fewer long-term health impairments. This is a general limitation as the author is not aware of any study that has investigated the effect of an automotive seating system in a longitudinal study. The challenge of such a study is certainly, that the seating system could be outdated by the time the results are available.

The IASS was tested in a passenger study in a standing vehicle, comparable to Hiemstra-van Mastrigt et al. (2015). Therefore, no study has yet examined the physiological effects of an IASS while driving. PDSS have been tested in real driving which also includes EMG measurements by Franz, Zenk, et al. (2011). Other authors investigated PDSS in the simulator (Durkin et al., 2006; Varela et al., 2019). In the future, physical effects of ADSS should also be investigated during driving, at least in the simulator. In the latter, vibrations as an influencing factor on EMG could be controlled quite well.

In this study the EMG data was not normalized using maximum voluntary contraction (MVC) measurements (Dankaerts et al., 2004). The IASS was investigated for the first time using EMG and the goal of the study was to provide a general understanding of the users' muscle activity. In order to reliably perform MVC measurements, participants should practice the isolated maximal muscle contractions before the study. The additional effort of training the contractions with the subjects beforehand seemed not appropriate at this point. Future research should investigate the intensity of the muscle contractions in more detail.

For organizational reasons, the sample included only male subjects. Professional drivers are particularly at high risk for sitting related health risks in automobiles due to long driving hours. Since a majority of professional drivers are male, the findings of the study are nevertheless valid for a large proportion of the affected individuals. According to a questionnaire answered by 20 companies from 13 European countries in 2015 for example, the share of women drivers in urban public transport was only 8.95 % (Europäische Akademie für umweltorientierten Verkehr gGmbH, 2016). In freight transport, the proportion of female professional drivers in Germany was around 1.8 % in 2018 (Bundesamt für Güterverkehr, 2019). However, in the interest of gender equality and the fact that efforts exist to attract women as drivers (Bundesamt für Güterverkehr, 2019), the IASS aims to be beneficial for women as well. The author is not aware that muscle activation patterns differ between men and women to such an extent that would critically limit the benefits of the IASS for women. However, the amplitude of activation for the individual muscles during the use of the IASS may differ in detail due to the different anatomies of the sexes (Da Cuña-Carrera et al., 2021). Predicting these differences, however, is difficult. For the shoulder sequence, a scapular retraction is performed in a sitting position. To the best of the author's knowledge, no studies have examined gender differences in muscle activation patterns during this movement. For the lumbar sequence, a draw-in maneuver should be performed in a sitting position. For the draw-in maneuver, there are studies that have examined gender differences in muscle activation, but only in supine and standing positions and with no clear results (Da Cuña-Carrera et al., 2021; Mannion et al., 2008; Manshadi et al., 2011; Rho et al., 2013). The exact amplitude of muscle activation is beyond the scope of this study.

In addition to MVC normalization, future studies that investigate the level of muscle activation should also include both genders to investigate possible differences.

Comfort and discomfort showed only marginal differences over time as well as between conditions. Even though the comparison of discomfort between the conditions became significant, the mean difference was rather small in this study. The small mean differences might be caused by the short study duration, for example Falou et al. (2003) found, that muscular discomfort occurs approximately after 2 sitting hours. An additional factor could be that high-end seats were used in the study, which already offer high comfort and elicit low levels of discomfort (Hiemstra-van Mastrigt et al., 2015; van Veen et al., 2015; Varela et al., 2019). Therefore, future studies with longer duration should be conducted to get a more accurate picture of how the IASS affects comfort and discomfort. Study II included longer sitting times, meaning that indications can already be drawn from this investigation. However, compared to professional drivers, who often sit for hours, the sitting time was comparatively short in Study II as well. In future studies it would also be interesting to use body maps as an evaluation technique (see Chapter 3.2). This might give a better understanding, if activity of specific muscles leads to less discomfort in these body regions.

The screen showing the user interface was slightly displaced to the left of the subjects. In a later series implementation, care should be taken to position the user interface preferably in front of the user in order to avoid possible muscular dysbalances caused by the one-sided rotation of the head. It is unlikely that the rotation of the head had a relevant effect on the activity of the muscles measured in this study. None of the captured muscles has the function to rotate the head (Drake et al., 2019). However, in order to completely exclude this influencing factor, the user interface should be positioned in front of the subject in future studies.

8.6 Conclusion

Sitting in general leads to various health risks, which are further, aggravated in vehicles due to restricted space in the cockpit. Now, primarily passive dynamic seating systems (PDSSs) are used to counteract the negative consequences of static sitting. Increasingly active dynamic seating systems

(ADSSs) that encourage the passenger to move himself are used as well. With continuing (partial-) automation appropriate secondary activities, such as ADSSs are expected to become more relevant in the future. This study compared the effect of the interactive seating system (ADSSs) with a massage seating system (PDSSs) on heart rate and muscle activity. The interactive seating system increased the heart rate and the muscle activity in all captured muscles. The massage seating system showed a tendency to lower the heart rate and the muscle activity only increased in the lower back. Based on this study, the IASS showed a substantially higher potential to reduce health risks of static sitting in the vehicle in comparison to the MS.

9. Conclusion

The aim of this thesis was to develop a seating system that counteracts both passive driver fatigue and health risks of static sitting in automobiles. In the automotive context, a general division can be made between passive dynamic seating systems and active dynamic seating systems. In the former, the user is passively mobilized, which includes for example massage seating systems. In the latter, however, the user performs movements himself. As physical activity is the most promising countermeasure against health risks of static sitting, active dynamic seating systems are expectedly advantageous in reducing these risks. However, current ADSSs use displays for interaction, which interferes with the driving task. Consequently, the use of these systems is restricted to passengers only. In order to circumvent this problem, a novel interactive seating system (IASS) was developed. The movement task is mediated through air bladders in the seat back, combined with an audio track that explains the movements. Feedback is given with ambient lighting and vibration elements in the seat cushion. Therefore, the driver's gaze can remain on the road while interacting with the system. As passive driver fatigue is most likely caused by monotony, performing adequate additional tasks while driving is proposed as a countermeasure in the literature. On this basis, it was assumed, that the use of the IASS might even improve driving performance under monotonous driving situations.

The IASS was compared with a state-of-the art massage seating system (MS) in two evaluation studies. These studies supported the hypothesis that the IASS is superior to the MS as a countermeasure against passive driver fatigue and health risks of static sitting in automobiles. The first study investigated both systems in a monotonous simulator ride. In the study, the IASS reduced passive driver fatigue, whereas the MS did not. The IASS was also preferred over the MS in terms of user experience and emotional perception. Additionally, comfort and discomfort benefited more from the IASS compared to the MS. In the second study, the increase in physical activity to reduce health risks of static sitting was evaluated with heart rate and muscle activity. Solely the IASS increased the heart rate. In addition, the IASS increased muscle activity in all six measured muscles. The MS on the other hand, only showed a tendency to increase the muscle activity in one muscle. Therefore, the IASS showed a substantially higher potential to reduce health risks of static sitting in automobiles in comparison to the MS.

With increasing partial automation in the future, greater efforts should be made to introduce anti-fatigue systems into series production vehicles. This relates to the interactive seating system, but also to the other promising solutions that are presented in the literature. Bier et al. (2019) also critize the lack of anti-fatigue systems in series production vehicles. The authors state that current technology is mostly limited to warning systems that indicate fatigue, but do not provide a solution for its prevention.

10. Outlook

The following two subchapters will provide an outlook for future work. Chapter 10.1 describes opportunities for further development of the IASS. Chapter 10.2 addresses further research questions.

10.1 Further development of the interactive seating system

Extension and individualization would be an important step to further increase the attractiveness but also efficacy of the interactive seating system. Above all, it would be desirable if the system would include additional exercises. Therefore, it is crucial, to identify additional movements that are useful from a physiological perspective and can be detected with the system at the same time. Currently, the different sequences of the interactive seating system are integrated into a structured program. In the future, these could be arranged in a random order combined with random inflation times of the air bladders to provide more variety. Such an increased variability might also improve the efficacy against PDF because the program could be adapted to the individual driver’s condition. The level of difficulty could be adjusted to the user, optimizing the relationship between task complexity and reduced monotony and thus keeping the driver in the optimal state. Therefore, it would be ideal to determine the current ‘training level’ of the user and adapt the program accordingly. This step, would allow the integration of the methodological structure ‘from easy to difficult’ into the IASS. If the system detects, that the user permanently interacts correctly with the system, it is possible to recommend a new and/or more difficult program. Ideally, the current driving situation should be taken into account as well.

Another improvement would be to recommend the use of the system based on the driver’s condition. For example, if an interior camera detects weariness via eye parameters, the IASS could be suggested as countermeasure by the vehicle.

Combining the IASS with interior cameras would also enable to survey if the user performs the movements correctly. The cameras could be used to monitor whether instructions, such as staying upright during the exercise are being followed.

In order to increase the motivation, it would also be desirable if physiological adaptions following the use of the IASS, such as increasing heart rate, were presented to the user. Heart rate can already be communicated to the vehicle today with the help of wearables (e.g. Mercedes-Benz, 2019). Such devices could also be used to capture the driver's breathing, since diaphragm breathing techniques are also a part of lumbar stabilization trainings (Akuthota & Nadler, 2004). The lumbar sequence of the IASS could then be expanded with breathing techniques including feedback.

Increasing (partial-) automation provides more freedom regarding the presentation of the interactive seating system. In the passenger scenario in Study III, a score bar was included as a simple gamification element, in order to increase the motivation. In dependence of the degree of automation, additional and more complex gaming elements could be added to the IASS also while driving. Thereby it is important to find the trade-off between higher motivation and distraction through the gaming elements.

10.2 Further research questions

Most importantly, the efficacy of the IASS against passive driver fatigue should be examined in studies with additional driving scenarios. Such studies should also examine more complex aspects of driving quality in addition to lane keeping. Besides studies in the driving simulator, the IASS should be tested in real driving in the future.

Another aspect might be to test whether the interaction modalities used by the IASS interfere with other functionalities in the vehicle. Especially mentioned should be lane departure warning systems that commonly use vibration as a warning signal. Some manufacturers use vibrations in the steering wheel (e.g. Mercedes-Benz, Volkswagen) others in the seat (e.g. Citroen) in order to alarm the driver (Bartels et al., 2015). Especially in the case of the latter, it is important to test for interferences if the IASS is used in parallel with such a system. For a better distinction of both signals, different types of vibration might be useful. In the future, lane departure warning system might become redundant, because these functions are taken over by the vehicle in the case of partial-autonomous driving. However, interference should be considered equally for all other warning systems.

Another factor that was not investigated in this thesis, but might be positively affected by the IASS, is driver boredom. Commonly the state of boredom is described as a high arousal state that occurs due to both over- and under stimulation (Raffaelli et al., 2018). Eastwood et al. (2012, p. 482) generally conceptualized boredom as “the aversive experience of wanting, but being unable, to engage in satisfying activity”. In the driving context, boredom leads to feelings of frustration, vigilance, relaxing, autopilot, mind wandering and discomfort (Steinberger et al., 2016). With a self-reported questionnaire, (Heslop, 2014) found out, that especially young drivers that are less conscientious and enthusiastic about driving are more prone to driver boredom. As a reaction to driver boredom, drivers use different coping mechanisms, which include approach and avoidance strategies (Steinberger et al., 2016). Approach strategies describe actions that add stimulation to the task, such as speeding. Avoidance strategies describe the participation in a secondary task such as using a smartphone while driving. In a study by Heslop (2014) boredom related strongly and positively to driver distraction but only weekly with self-reported speed. Therefore, it can be assumed that avoidance strategies, i.e. secondary tasks are more frequently chosen than approach strategies. That cell phone use while driving is an alarming problem, was for example shown through a study by Vollrath et al. (2016). The authors observed passing vehicles from the roadside and detected that 4.5 % of the drivers were using a smartphone (e.g. typing), 2.2 % were calling with a handheld phone and 1.7 % with a hands free phone. The risks might be further aggravated if drivers hide their smartphone below the car’s windows while using it, to avoid being caught by police, as phone use is illegal. As a result, the view is completely taken off the road. Suitable secondary tasks, such as the IASS, might be a good measure to reduce driver boredom and consequently the execution of inappropriate secondary tasks. However, it can be assumed that various factors and not just boredom motivate for inappropriate secondary tasks while driving. Therefore, further research would be necessary to understand the consequences of offering suitable secondary tasks on the engagement in unsuitable secondary tasks while driving.

The phenomenon of monotony-related fatigue is not limited to driving. Other monotonous occupations may also benefit from the performance of a secondary motor task. In the future, the use of the IASS could be studied especially in other sedentary jobs in the transportation industry. This includes for example air traffic controllers (Straussberger et al., 2005), ship crews (Bielić & Zec, 2004), and train drivers (Dunn & Williamson, 2021).

In this thesis, muscle activity and heart rate were captured to investigate health-promoting effects against prolonged sitting of the IASS. Another health-promoting effect might be generated through varying pressure on the vertebrae. In general, the compressing forces through sustained sitting are associated with a loss if spinal height (Billy et al., 2014; Kourtis et al., 2004). This loss of height can be reduced with activity interventions. For example Billy et al. (2014) measured spinal health with midsagittal lumbar magnetic resonance after four hours of sitting. Without any intervention, disc height at L4-5 significantly decreased, whereas this was not the case with a position and stretching protocol. In the study of Kourtis et al. (2004) it was possible to prevent the loss of spinal height with hyperextension interventions. Dynamic compressions through such movements are associated with increased oxygen concentration, reduced lactate accumulation in the intervertebral disc (Huang & Gu, 2008).

In addition, the IASS might also have a positive influence on venous thromboembolism. This disorder can be caused by blood pooling in the legs due to sitting immobility. According to Porter et al. (2003) especially the area around the ischial tuberosity can be exposed to high pressures during sitting, which is sufficient to reduce blood circulation through the capillaries. For example Hitosugi et al. (2000) found increased blood viscosity from a foot vein after two hours of sitting, which according to the authors, can increase the local thrombotic tendency in the leg. In another study, conducted by Hitos et al. (2007) the blood volume flow in the popliteal vein was reduced by almost 40 % after sitting for 100 minutes. In a meta-analysis by Chandra (2009) a clear dose-response relationship was found, with an increasing risk for venous thromboembolism of 18 % for every additional 2 hours of travel; when traveling by airplane, the risk even increased by 26 %. Regardless of the type of travel, Cannegieter et al.

(2006) found twice the risk of venous thromboembolism (odds ratio 2.1, 95% confidence interval 1.5-3.0) for individuals who had traveled for more than four continuous hours at least once within 8 weeks before the onset of venous thromboembolism. This finding is in accordance with the statement by the World Health Organization (2012), that epidemiological studies show that more than 4h of travel increases the risk for venous thromboembolism two- to threefold.

The likelihood for developing venous thromboembolism is influenced by a narrow-seat pitch, but particularly aggravated trough pre-existing risk for thrombotic conditions (Lippi & Favaloro, 2018). The authors add that ‘car thrombosis’ might be rather a trigger than a risk factor for venous thrombosis. In most cases, the blood clots are only small and do not lead to any complaints (World Health Organization, 2012). An extended overview of risk factors is given in (Schobersberger et al., 2008; World Health Organization, 2012).

There is consensus in the literature regarding measures against travel-related venous thromboembolism. Preventive medication does not appear to be appropriate in healthy individuals (Lippi & Favaloro, 2018). Chandra (2009) state, that even in the case of a three-fold relative risk, the absolute likelihood of developing venous thromboembolism is too low to justify possible side effects. However, it is considered reasonable to perform precautionary measures with no or very little side effects (Lippi & Favaloro, 2018). This primarily includes moving while traveling. The World Health Organization (2012) lists muscle contractions as a crucial factor to improve blood flow in the veins, particularly in the legs. When moving around is not possible, at least movements in the seat should be executed. Especially leg exercises are mentioned (Schobersberger et al., 2008) that include activation of the calf muscles (World Health Organization, 2012). Hitos et al. (2007) found that such exercises significantly increase blood volume, with increasing efficacy for increasing resistance.

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Appendices

Appendix A

Influencing factors of task complexity

Table 25: *Adopted list of influencing factors of task complexity from (P. Liu & Li, 2012).*

Task components	Complexity contributory factors
Goal/Output	Clarity Quantity Conflict Redundancy Change
Input	Clarity Quantity Diversity Inaccuracy Rate of Change Redundancy Conflict Unstructured guidance Mismatch Non-routine events
Process	Clarity Quantity of paths Quantitiy of action/steps Conflict Repetiveness Cognitive requirements by an action Physical requirements by an action
Time	Concurrency Pressure
Presentation	Format Heterogeneity Compatibility

Appendix B

Detailed characteristics of the route design in Study II

Table 26: *Details of the route design in Study II. The list from Bier et al. (2019) served as template.*

	Category	Characteristics	Specification
Track	Track layout	Design	Circular, radius 9.4 km
		Vertical track routing	Perfectly flat
	Track type	Track type	Motorway
		Number of lanes in own driving direction	3
		Lane width	3,5 m
	Connections	Junctions	None
		Parking spaces	None
		Bridges	None
	Markings	Road signs	None
		Road markings	Between lanes: dashed white lines; Outer lane: solid white lines;
		Emergency lane	No
		Central reservation	No
		Delineator	No
		Crash barrier	Only on the left side
Landscape	Topography	-	Plain landscape
	Meteorology	Weather	No precipitation; Sky blue - cloudy
		Daytime	By day
		Fog	No
		Season	Summer or summer-like
	Type of landscape	Tree density	No trees
		Water bodies	No water bodies
Traffic	Traffic density: Distance between vehicles	Left lane	666 meters
		Right lane	375 meters
	Traffic participants	Cars	Yes
		Trucks	Yes (only right lane)
		Pedestrians	No
	Traffic speed	Left lane	82 km/h
		Right lane	42 km/h
		Oncoming traffic	None

Appendix C

Results of the test for normal distribution of the data from Study II

Table 27: *Results of the Shapiro-Wilk test of all data sets from Study II.*

	AC	PC	CC
SDLP *Prae*	p <.05	p <.05	p =.07
SDLP *Int.*	p =.052	p <.05	p <.05
SDLP *Post*	p <.05	p <.05	p <.05
MDFL *Prae*	p <.05	p <.05	p <.05
MDFL *Int.*	p <.05	p <.05	p <.05
MDFL *Post*	p <.05	p <.05	p <.05
SDSA *Prae*	p <.05	p <.05	p =.355
SDSA *Int.*	p <.05	p <.05	p <.05
SDSA *Post*	p <.05	p <.05	p <.05
HR *Prae*	p = .432	p < .05	p = .228
HR *Int.*	p = .960	p = .081	p = .226
HR *Post*	p = .452	p = .107	p = .329
HRV *Prae*	p < .05	p < .05	p < .05
HRV *Int.*	p < .05	p < .05	p < .05
HRV *Post*	p < .05	p < .05	p < .05
EDA *Prae*	p = .316	p < .05	p = .889
EDA *Int.*	p < .385	p < .05	p < .973
EDA *Post*	p < .05	p < .05	p = .894
EO *Prae*	p = .206	p = .556	p = .296
EO *Int.*	p = .442	p = .221	p = .334
EO *Post*	p = .122	p = .976	p = .744
BF *Prae*	p = .331	p = .308	p = .502
BF *Int.*	p < .05	p < .05	p < .05
BF *Post*	p < .05	p < .05	p < .05
BD *Prae*	p = .726	p = .108	p = .642
BD *Int.*	p = .995	p = .974	p = .986
BD *Post*	p = .429	p = .558	p = .885
PD *Prae*	p = .096	p = .438	p < .05
PD *Int.*	p < .05	p = .066	p < .05
PD *Post*	p < .05	p = .384	p < .05

Appendix D

Results for the ANOVAs from Study II

Table 28: *Results of the ANOVAs for standard deviation of lane position (SDLP), mean departure from lane (MDFL), standard deviation of steering angle (SDSA), heart rate (HR), heart rate variability (HRV), skin conductance level (SCL), eyelid distance (ED), blink frequency (BF), blink duration (BD), pupil diameter (PD).*

		F	Df$_1$	Df$_{error}$	Sig.	Partial η^2
SDLP	TI	10.64	1.36	46.15	p = .001	.24
	Condition	6.72	1.44	48.80	p = .006	.17
	TI * cond.	3.59	2.18	74.19	p = .029	.10
MDFL	TI	4.22	1.31	44.47	p = .036	.11
	Condition	2.20	1.07	36.49	p = .14	.06
	TI * cond.	1.84	1.19	40.62	p = .18	.05
SDSA	TI	9.61	2	68	p < .001	.22
	Condition	0.48	2	68	p = .624	.01
	TI * cond.	9.46	3.29	111.92	p < .001	.22
HR	TI	23.81	2	62	*p* < .001	.43
	Condition	5.69	2	62	*p* = .005	.16
	TI * cond.	29.22	2.15	66.71	*p* < .001	.49
HRV	TI	1.43	1.33	41.26	p = .248	.04
	Condition	1.03	2	62	p = .363	.03
	TI * cond.	0.83	2.31	71.65	p = .454	.03
SCL	TI	10.71	1.46	45.39	p = .001	.26
	Condition	0.29	2	62	p = .75	.01
	TI * cond.	4.77	2.53	78.35	p = .007	.13
ED	TI	2.49	2	64	p = .006	.15
	Condition	6.44	2	64	p = .003	.17
	TI * cond.	5.21	4	128	p = .001	.14
BF	TI	0.36	1.41	44.97	p = .62	.01
	Condition	0.41	1.67	53.55	p = .63	.01
	TI * cond.	1.32	2.99	95.58	p = .27	.04
BD	TI	6.27	2	64	p = .003	.16
	Condition	1.43	2	64	p = .25	.04
	TI * cond.	0.83	4	128	p = .51	.03
PD	TI	0.20	1.68	53.76	p = .78	.01
	Condition	3.26	1.61	51.39	p = .057	.09
	TI * cond.	1.74	2.65	84.74	p = .17	.05

Appendix E

Mean values and variances from Study II

Table 29: *Mean values ± standard deviation in the active (AC), passive (PC) and control condition (CC).*

		AC	PC	CC
SDLP	*Prae*	0.27 ± 0.08	0.28 ± 0.10	0.29 ± 0.09
	Int.	0.23 ± 0.07	0.30 ± 0.13	0.30 ± 0.11
	Post	0.28 ± 0.09	0.35 ± 0.23	0.31 ± 0.10
MDFL	*Prae*	0.65 ± 0.91	0.70 ± 1.33	0.70 ± 1.07
	Int.	0.43 ± 0.69	1.29 ± 3.00	1.10 ± 2.37
	Post	0.70 ± 1.29	2.43 ± 7.08	1.18 ± 1.68
SDSA	*Prae*	0.81 ± 0.35	0.78 ± 0.37	0.77 ± 0.35
	Int.	0.90 ± 0.38	0.81 ± 0.42	0.89 ± 0.46
	Post	0.73 ± 0.28	0.97 ± 0.56	0.93 ± 0.49
HR	*Prae*	68.7 ± 9.9	69.3 ± 9.6	68.7 ± 8.6
	Int.	74.0 ± 9.7	68.9 ± 9.5	69.2 ± 8.2
	Post	70.5 ± 9.5	70.3 ± 9.5	69.8 ± 8.4
HRV	*Prae*	42.65 ± 23.44	42.05 ± 21.59	46.45 ± 24.15
	Int.	42.84 ± 22.19	40.72 ± 20.14	43.08 ± 23.64
	Post	39.15 ± 18.96	42.96 ± 21.49	43.05 ± 23.18
SCL	*Prae*	0.74 ± 0.33	0.80 ± 0.41	0.76 ± 0.29
	Int.	0.96 ± 0.38	0.87 ± 0.40	0.83 ± 0.30
	Post	0.80 ± 0.35	0.95 ± 0.51	0.90 ± 0.33
ED	*Prae*	8.77 ± 2.21	8.58 ± 2.29	8.64 ± 2.12
	Int.	9.23 ± 2.28	8.21 ± 2.41	8.22 ± 2.12
	Post	8.65 ± 2.08	8.25 ± 2.22	8.15 ± 2.01
BF	*Prae*	18.07 ± 10.83	18.48 ± 13.17	18.43 ± 13.73
	Int.	20.05 ± 13.06	17.35 ± 11.44	18.70 ± 13.15
	Post	18.12 ± 9.63	17.61 ± 9.06	18.07 ± 10.81
BD	*Prae*	388.62 ± 63.18	398.66 ± 73.48	388.93 ± 76.17
	Int.	408.39 ± 74.71	412.42 ± 71.38	400.26 ± 74.89
	Post	389.65 ± 70.49	401.76 ± 71.70	399.46 ± 75.17
PD	*Prae*	4.74 ± 1.25	4.88 ± 1.36	4.68 ± 1.37
	Int.	4.66 ± 1.25	5.13 ± 1.66	4.64 ± 1.37
	Post	4.74 ± 1.26	4.93 ± 1.36	4.69 ± 1.42

Appendix F

Figures showing skin conductance depending on time of day

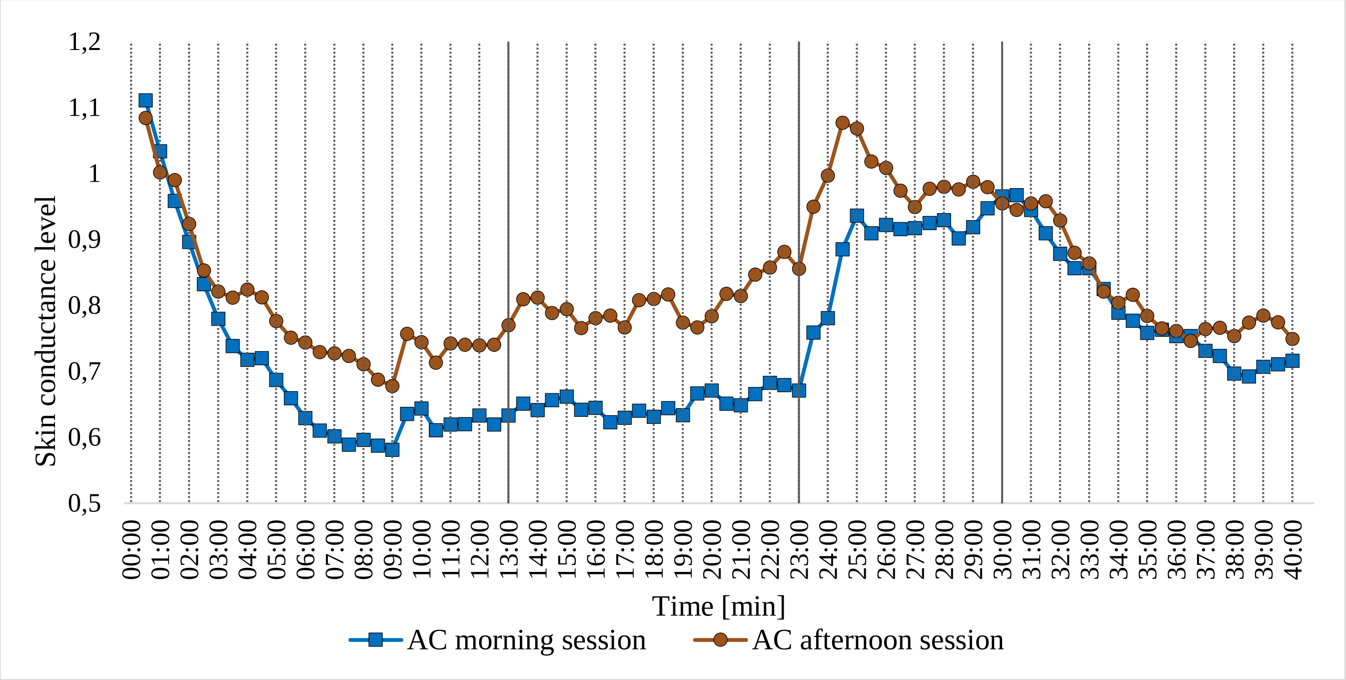

Figure 57: *Development of skin conductance in the active condition in Study II. The curves are plotted separately for subjects in the morning and afternoon session.*

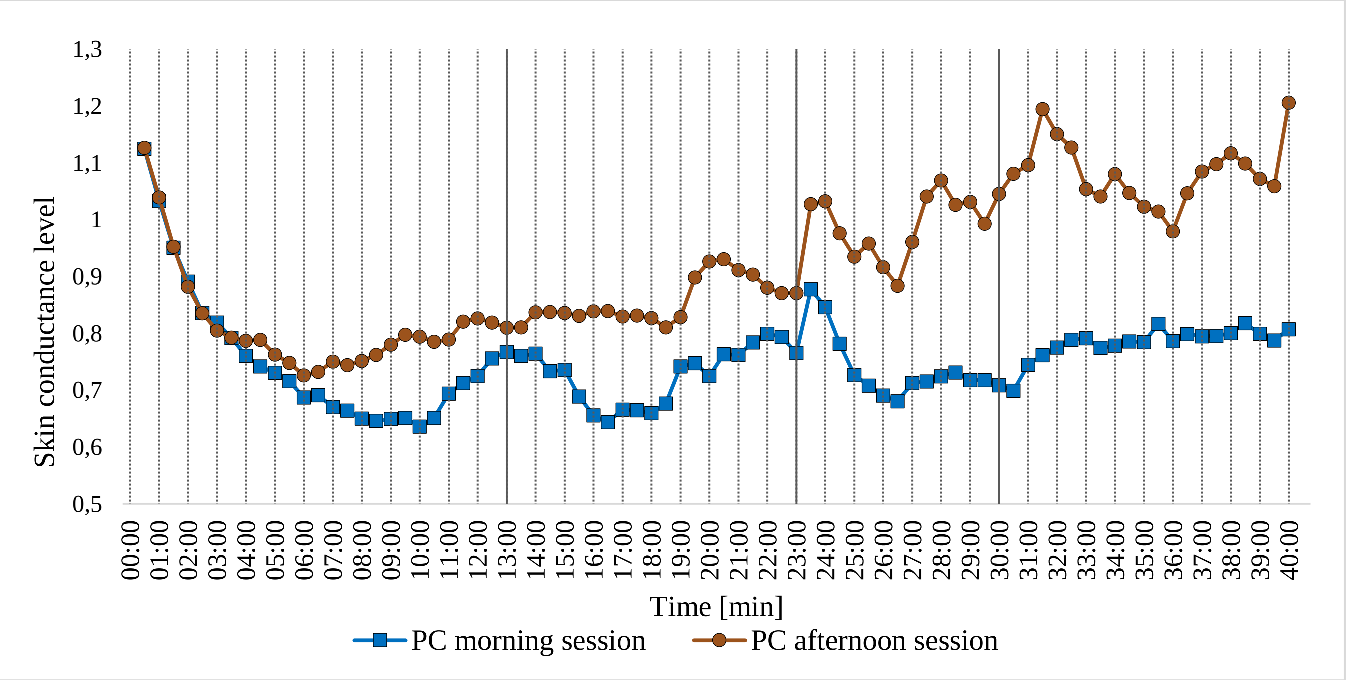

Figure 58: *Development of skin conductance in the passive condition in Study II. The curves are plotted separately for subjects in the morning and afternoon session.*

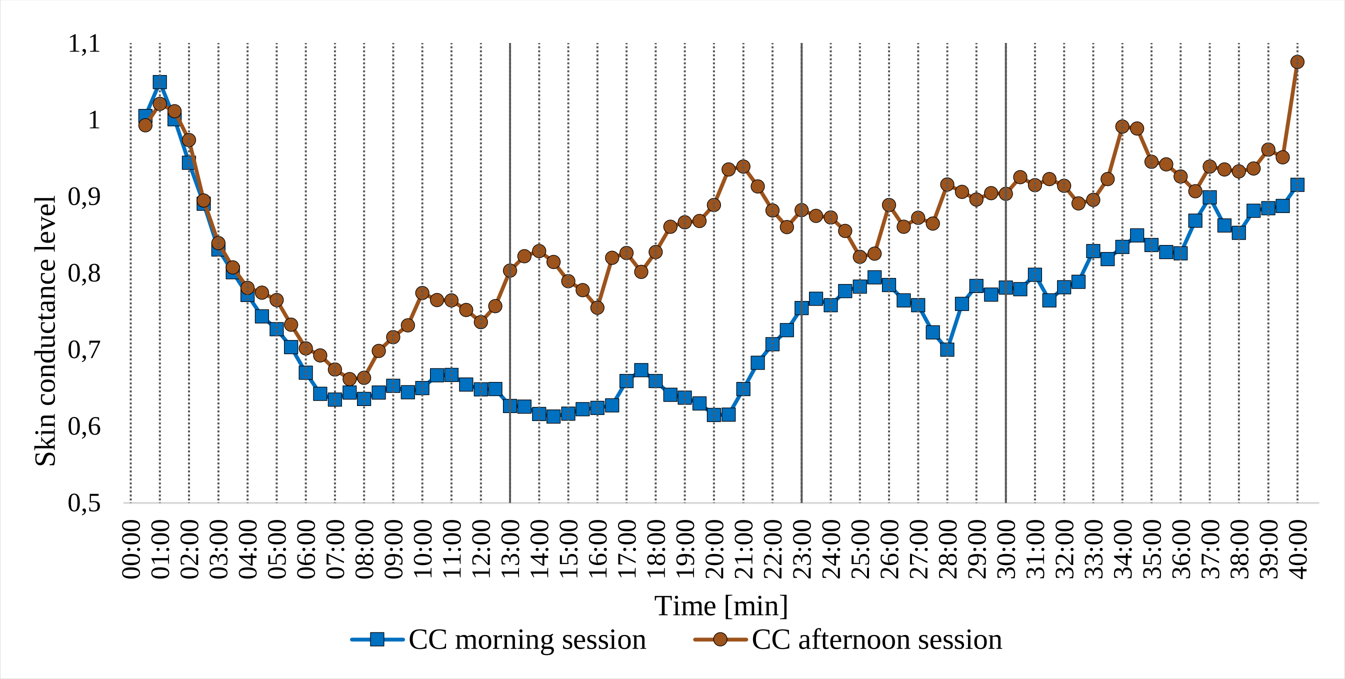

Figure 59: *Development of skin conductance in the control condition in Study II. The curves are plotted separately for subjects in the morning and afternoon session.*

Appendix G

Detailed description of the EMG electrode attachments from Study III

According to (Hermens et al., 2000), the specification of the electrode positioning includes the location as well as the orientation. The location gives information where the electrodes have to be attached to the muscle. The orientation describes where the axis runs between the two electrodes. Electrodes were placed on the left side of the body in the direction of the subject's gaze.

Table 30: *Detailed positioning of the electromyography electrodes in Study III.*

Muscle	Location	Orientation	Reference
M. gluteus maximus	At 50 % on the line between the sacral vertebrae and the greater trochanter.	On the line from the posterior superior iliac spine to the middle of the posterior aspect of the thigh.	(SENIAM, 2020)
M. longissimus	At 2 finger width lateral from the proc. spin. of L1.	Vertical in seated position.	(SENIAM, 2020)
M. obliquus internus abdominis	2 cm lower the most prominent point of the ASIS; just medial and superior to the inguinal ligament.	Inclined 6° inferomedially to the horizontal from the inguinal ligament.	(Boccia & Rainoldi, 2014)
M. rectus abdominis	2 cm lateral of the navel, the center of the caudal electrode 1 cm cranial to the navel.	Vertical.	(Huebner et al., 2015; Ng et al., 2002)
M. trapezius pars ascendens	At 2/3 on the line from the trigonum spinea to the 8th thoracic vertebra.	On the line between T8 and the acromion.	(SENIAM, 2020)
M. trapezius pars transversa	50 % between the medial border of the scapula and the spine, at the level of T3.	On the line between T5 and the acromion.	(SENIAM, 2020)

Appendix H

Results of the test for normal distribution of the data from Study III

Table 31: *Results of the Shapiro-Wilk test of all data sets from Study III.*

	Active	Passive
Heart rate *Prae*	p = .154	p = .199
Heart rate *Int.*	p = .098	p = .223
Heart rate *Post*	p = .212	p = .167
M. gluteus maximus *Prae*	p < .05	p < .05
M. gluteus maximus *Lumbar*	p < .05	p < .05
M. gluteus maximus *Shoulder*	p < .05	p < .05
M. gluteus maximus *Post*	p < .05	P < .05
M. longissimus *Prae*	p < .05	p < .05
M. longissimus *Lumbar*	p < .05	p < .05
M. longissimus *Shoulder*	p < .05	p < .05
M. longissimus *Post*	p < .05	P < .05
M. obliquus abdominis *Prae*	p < .05	p < .05
M. obliquus abdominis *Lumbar*	p < .05	p < .05
M. obliquus abdominis *Shoulder*	p < .05	p < .05
M. obliquus abdominis *Post*	p < .05	P < .05
M. rectus abdominis *Prae*	p < .05	p < .05
M. rectus abdominis *Lumbar*	p < .05	p < .05
M. rectus abdominis *Shoulder*	p < .05	p < .05
M. rectus abdominis *Post*	p < .05	P < .05
M. trapezius pars ascendens *Prae*	p < .05	p < .05
M. trapezius pars ascendens *Lumbar*	p < .05	p < .05
M. trapezius pars ascendens *Shoulder*	p < .05	p = .076
M. trapezius pars ascendens *Post*	p < .05	P < .05
M. trapezius pars tranversalis *Prae*	p < .05	p < .05
M. trapezius pars tranversalis *Lumbar*	p < .05	p < .05
M. trapezius pars tranversalis *Shoulder*	p < .05	p = .262
M. trapezius pars tranversalis *Post*	p < .05	P < .05

Appendix I

Mean values and variances of heart rate from Study III

Table 32: *Mean ± standard deviation of heart rate in the conditions.*

	Active condition	Passive condition
Heart rate *Prae*	66.0 ± 11.4	65.7 ± 10.7
Heart rate *Int.*	74.6 ± 12.3	65.1 ± 10.6
Heart rate *Post*	67.2 ± 12.1	66.5 ± 10.9

Appendix J

Complete results of the ANOVAs from Study III

Table 33: *Results of the ANOVAs from Study III.*

Measure		F	Df$_1$	Df$_{error}$	Sig.	Partial η^2
	TI	35.04	1.59	42.96	$p < .001$	.57
Heart rate	Condition	41.26	1	27	$p < .001$	.60
	TI * cond.	45.91	1.43	38.72	$p < .001$	.63
	TI	17.83	1.10	29.74	$p < .001$	.40
M. GM	Condition	22.82	1	27	$p < .001$	.46
	TI * cond.	17.59	1.10	29.70	$p < .001$	.39
	TI	89.79	1.16	31.32	$p < .001$	.77
M. LO	Condition	53.79	1	27	$p < .001$	.67
	TI * cond.	72.97	1.18	31.75	$p < .001$	.73
	TI	21.09	1.86	50.24	$\mathrm{p} < .001$	.44
M. OIA	Condition	39.74	1	27	$\mathrm{p} < .001$	.59
	TI * cond.	21.97	1.82	49.20	$\mathrm{p} < .001$	.45
	TI	11.96	1.15	31.03	$p = .001$	.31
M. RA	Condition	12.82	1	27	$p = .001$	.32
	TI * cond.	12.05	1.15	31.11	$p = .001$	.31
	TI	24.43	1.05	28.36	$p < .001$	.47
M. TPA	Condition	23.38	1	27	$p < .001$	.46
	TI * cond.	25.34	1.05	28.47	$p < .001$	.48
	TI	21.30	1.03	27.75	$p < .001$	.44
M. TPT	Condition	22.91	1	27	$p < .001$	.46
	TI * cond.	21.50	1.03	27.74	$p < .001$	.44

Appendix K

Exact results of muscle activity and post hoc comparisons between conditions from Study III

Table 34: *Mean ± standard deviation of muscle activity in the conditions. Additionally significant results with p < .05 of the post hoc comparisons between conditions are listed with the effect size (Cohen's d).*

Muscle	Time interval	AC	PC	95% CI		Sig. (| *d* |)
				Lower	Upper	
M. GM	Prae	1.30 ± 0.54	1.27 ± 0.57			
	Lumbar	2.13 ± 1.28	1.26 ± 0.56	0.36	1.37	p = .002 (0.66)
	Shoulder	5.93 + 5.53	1.28 ± 0.56	2.49	6.81	p < .001 (0.83)
	Post	1.25 ± 0.45	1.27 ± 0.56			
M. LO	Prae	3.84 ± 2.38	3.31 ± 2.00			
	Lumbar	3.83 ± 1.95	3.73 ± 2.28			
	Shoulder	22.26 + 11.02	5.14 ± 3.23	13.04	21.19	p < .001 (1.63)
	Post	3.69 ± 2.27	3.57 ± 1.79			
M. OIA	Prae	1.97 ± 1.51	1.76 ± 1.40			
	Lumbar	7.85 ± 6.53	1.59 ± 1.06	3.87	8.66	p < .001 (1.01)
	Shoulder	10.37 + 9.42	1.56 ± 0.91	5.44	12.17	p < .001 (1.02)
	Post	1.91 ± 1.29	1.60 ± 0.77			
M. RA	Prae	1.78 ± 1.09	1.75 ± 1.26			
	Lumbar	5.79 ± 5.90	1.72 ± 1.19	1.76	6.37	p = .001 (0.68)
	Shoulder	2.65 + 1.93	1.72 ± 1.16	0.21	1.65	p = .013 (0.50)
	Post	1.74 ± 0.86	1.72 ± 1.09			
M. TPA	Prae	3.27 ± 1.77	2.98 ± 1.73			
	Lumbar	8.06 ± 9.71	2.83 ± 1.11	1.63	8.83	p = .006 (0.56)
	Shoulder	47.78 ± 47.74	2.78 ± 1.05	26.68	63.30	p < .001 (0.95)
	Post	3.60 ± 2.48	3.25 ± 1.92			
M. TPT	Prae	2.61 ± 1.37	2.28 ± 0.78			
	Lumbar	5.22 ± 5.17	2.35 ± 0.71	0.99	4.75	p = .004 (0.59)
	Shoulder	37.04 + 39.36	2.42 ± 0.77	19.52	49.72	p < .001 (0.89)
	Post	2.62 ± 1.23	2.46 ± 1.12			

Appendix L

Exact results of the post hoc comparisons of muscle activity within conditions from Study III

Table 35: *The p-values for the significant post-hoc comparisons within conditions (with p < .05) are listed with the effect size (Cohen's d) in brackets.*

Muscle	AC Prae/Lumbar	AC Prae/Shoulder	AC Lumbar/Shoulder	AC Lumbar/Post	AC Shoulder/Post
M. GM	p < .001 (0.63)	p = .001 (0.84)	p = .006 (0.70)	p < .001 (0.68)	p < .001 (0.85)
M. LO		p < .001 (1.69)	p < .001 (1.89)		p < .001 (1.82)
M. OIA	p < .001 (0.94)	p < .001 (1.02)		p < .001 (0.96)	p < .001 (1.01)
M. RA	p = .008 (0.68)		p = .022 (0.60)	p = .006 (0.70)	p = .036 (0.56)
M. TPA	p = .040 (0.55)	p < .001 (0.96)	p < .001 (0.96)		p < .001 (0.95)
M. TPT	p = .037 (0.56)	p < .001 (0.90)	p = .001 (0.85)		p < .001 (0.88)
	PC Prae/Shoulder	PC Lumbar/Shoulder	PC Shoulder/Post		
M. Long	p < .001 (0.91)	p < .001 (0.89)	p = .005 (0.71)		