# Enhancing the Vigilance of Car Drivers: a Review on Fatigue Caused by the Driving Task and Possible Countermeasures

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## ABSTRACT

Before fatigue caused by the driving task becomes a safety threat, it already has a negative effect on well-being. Therefore, it is desirable to intervene in an early stage of the fatiguing process to decrease the perceived load from a monotonous driving task and to create a more pleasurable driving experience. Enhancing driver vigilance could also create a competitive advantage for the car manufacturer. This paper reviews the existing body of knowledge concerning driver fatigue theories and countermeasures against driver fatigue. Current (automotive) features concerning fatigue are also evaluated. A fatigue countermeasure system should measure and/or predict fatigue, intervene with a stimulus and subsequently restore performance and alertness. A distinction can be made between physical and cognitive fatigue. Physical fatigue results mainly from static sitting issues. This type of fatigue can be countered with micro-movements and the stimulation of postural change. Cognitive fatigue can be further divided into task-related and sleep-related fatigue. Fatigue resulting from task overload can be countered with automation and assist systems. Fatigue from task underload can be countered with a variety of stimulation. Sleep-related fatigue is considered intervention resistant by some researchers, although it also seems to be possible to manipulate the circadian rhythm with blue light.

**Keywords:** driver fatigue, countermeasures, comfort

## INTRODUCTION

Driver fatigue is often quoted as a causal factor in accidents (Ahlstrom et al., 2013; Horne and Reyner, 2001). Before becoming an actual threat to safety, however, fatigue caused by the driving task also has a negative effect on well-being when the driver becomes drowsy in the course of a trip. Enhancing driver vigilance in order to increase comfort is not only beneficial for the user, but could also create a competitive advantage for the car manufacturer.

Therefore, it would be desirable to already intervene in an early stage of the fatiguing process in order to decrease the perceived load from the monotonous driving task and create a more pleasurable driving experience. In order to understand how fatigue is established, different types of fatigue and their causes according to literature research are evaluated. Next, existing countermeasures on these causal factors as well as promising theories providing starting points for countermeasures are discussed. This results in a theoretical framework for driver vitalization and its countermeasures. Finally, the measurable effects of fatigue countermeasures are evaluated.



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# METHOD

A literature review was conducted, focusing on research concerning driver fatigue theories and the different focuses on driver fatigue, studies on possible countermeasures against these different types of fatigue, as well as studies on different methods for measuring fatigue. Furthermore, current automotive features concerning fatigue and safety were evaluated. The publications used for the literature review were retrieved with a search in Scopus in the period of March to August 2013.The following keywords or a combination of these keywords were used for the search: “driver” OR “car” OR “vehicle” AND “fatigue” OR “cognitive fatigue” OR “physical fatigue” OR “discomfort” OR “vitalization” OR “vigilance” OR “refreshment” OR “countermeasures”. Papers considering driver fatigue in relation to shift work specifically were left out of account since they focus rather on circadian rhythm issues. Relevant references from the selected articles were also reviewed, leading to a subsequent search on the keywords “micro-movements”, “macro-movements”, “seating” AND “discomfort”, and “sympathetic nervous system activation”.

# DRIVER FATIGUE THEORY

The manifestation of driver fatigue is a process influenced by several factors. The distinction of different factors contributing to driver fatigue is important in order to evaluate measures for fatigue detection and countering (May and Baldwin, 2009). Thus, this knowledge is important for car manufacturers as the starting point of the development of fatigue countermeasures.

Grandjean (1979) distinguishes mental fatigue, boredom and physical fatigue. Physical fatigue consists of discomfort from overstressed muscles, whereas mental fatigue results in weariness caused by the cognitive aspects of a task. Boredom occurs when there is little to no demand. Hancock and Desmond (2001) determine two types of fatigue. The first, active fatigue, is derived from lasting perceptual-motor response requirements of the driving task. The second, passive fatigue, results from system monitoring with either little or no perceptual-motor response requirements. Hancock and Desmond (2001) also point out that fatigued drivers are especially at risk when demand is low.

There are also two types of fatigue according to May and Baldwin (2009): sleep-related fatigue and task-related fatigue. Sleep-related fatigue ensues from sleep deprivation, extended duration of a need for alertness and circadian rhythm effect. Circadian is relating to a period of 24 hours, especially to the changes in people’s or animals’ bodies that happen during this period (Macmillan English Dictionary, 2007). Task-related fatigue can be further subdivided into fatigue either caused by mental overload or underload: a similar distinction as Grandjean’s mental fatigue and boredom (1979). Vigilance (Parasuraman et al., 1998) is a general state of wakefulness characterized as arousal or alertness. Environmental factors influencing vigilance are noise, vibration, ambient temperature, frequency and variety of stimulation, as well as environmental pollutants.

The theory provided here forms the foundation for the framework presented in figure 1. This framework distinguishes between physical and cognitive fatigue and their different causes, further explained in the sections 3.1 and 3.2. In reality, however, it seems to be the case that driver fatigue does not purely establishes itself in the form of one of these types of fatigue. As is the case with well-being in general (according to the comfort model of De Looze et al., 2003), fatigue probably develops from a combination of several contextual factors such as the embodiment of cockpit and seat, task duration and intensity, emotional and physical state of the driver, and goal of the drive. The bottom of the figure shows several measures for counteracting the different types of fatigue, which are discussed in section 4.

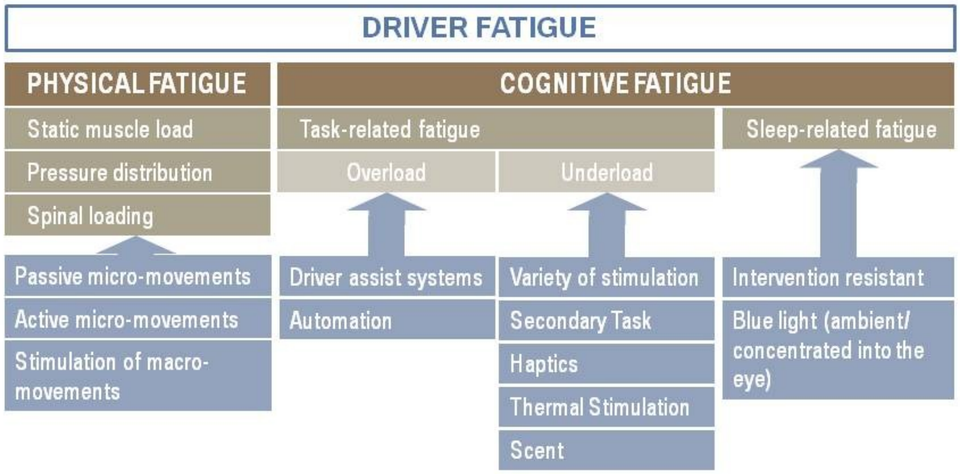


Fig. 1 Driver fatigue model

## Physical fatigue

In the case of driving a car, physical fatigue is related to perceptual-motor adjustments specific to the driving task (holding and operating the steering wheel, using the foot levers) and to discomfort caused by prolonged sitting. Prolonged sitting is associated with several types of discomfort and, in general, it is encouraged to periodically engage in non-sedentary activities (Beach et al., 2005). Ebe and Griffin (2000) argue that in cars discomfort is mainly influenced by the static seat characteristics and that vibration can be ruled out as an influence of physical fatigue in high quality cars. De Looze et al. (2003) propose three seat characteristics influencing discomfort that can be measured objectively: pressure distribution, muscle activity and lumbar curvature. This is in agreement with the main factors contributing to driver fatigue according to Grujicic et al. (2010): the maximum level of muscle activity and the number of muscles activated, shear force and spinal force.

Previous studies have already developed an ideal pressure distribution for a car seat with minimal pressure in the intervertebral discs (Zenk, 2008). Furthermore, it is generally accepted that continuous, static muscle activity results in discomfort (e.g. Falla et al., 2007). Also, flexed lumbar spine postures can result in an increase in the relative contribution of the passive tissues to holding the torso upright during sitting (Beach et al., 2005). Despite the elaborate efforts to develop the ideal seat in the automotive field as well as in other fields (i.e. office furniture), an often stated hypothesis is that movement or frequent posture change is desirable in order to improve seating comfort (Lueder, 2003). Graf et al. (1995) suggest that natural movements are desirable and necessary as long as they are within an acceptable range. Leuder (2003) stresses the importance of variation between severable stable and healthy body postures.

Several studies on seating in general describe a relation between seating time, discomfort and body movement. Telfer et al. (2009) found that subjective discomfort and movement increase over time. The amount of movement was found to be greater in chairs rated most uncomfortable. Vergara and Page (2002) propose that macro-movements are a good indicator of discomfort. Fujimaki and Noro (2005) also found discomfort to increase over time, but argue that macro-movements occur in order to decrease discomfort in a repeating pattern during prolonged sitting. In agreement with this statement, Graf et al. (1995) already found that work tasks which resulted in more musculo-skeletal disorders allowed for less frequent and less marked postural change. Finally, Callaghan and McGill (2001) suggest that humans redistribute their muscular loads according to their comfort level using posture adjustment.

Studies focusing specifically on physical fatigue when driving concluded similar findings. Lee (1995), for instance, found that the driver moves more frequently when he/she feels uncomfortable. Na et al. (2005) found significantly more discomfort after driving in a simulator for 45 minutes. During this study, a correlation between body pressure variation and subjective discomfort was also discovered. Furthermore, Cheng et al. (2011) found that during long-time driving, people either bend forward or slouch down. However, Falou et al. (2003) measured EMG in two



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different car seats without a driving task for 150 minutes with and without added vibration and found no significant difference over time. Muscle fatigue should result in compressed EMG signals or frequency changes in the EMG frequency spectrum (Hagg et al., 2000).

### Cognitive fatigue

As suggested by May and Baldwin (2009), cognitive fatigue is either caused by overload or underload of the driving task or caused by sleep deprivation and circadian rhythm. Sleep-related fatigue is considered intervention resistant by these researchers. Task demand and duration exclusively can produce task-related fatigue without the contribution of any sleep-related factors. Task overload relates to an intense and perhaps stressful task, whereas task underload relates to a monotonous, monitoring task. It is possible to prevent fatigue from task underload and enhance vigilance by offering driver stimulation, since "environmental factors influencing vigilance are … frequency and variety of stimulation" (Parasuraman et al., 1998).

There is no consensus on the amount of driving time needed for task-related fatigue to establish. Nilsson et al. (1997) evaluated the maximum amount of time one could drive in a simulator and found quitting time to lie between 90 and 240 minutes. However, Liu and Wu (2009) found that fatigue is produced after 60 minutes of driving and surprisingly found no difference between monotonous or complex roads. Unlike Thiffault and Bergerson (2003), who found that a monotonous road side has a negative effect on the driving performance as well as a time-on-task effect on fatigue. This corresponds with previously described theories on driver fatigue. However, there seem to be difficulties when distinguishing task-related fatigue from overload or underload and, in reality, it seems to be the case that a combination of these three occurs.

## FATIGUE COUNTERMEASURES

### Literature on countermeasures against cognitive fatigue

Most literature discussing driver fatigue countermeasures focuses on cognitive fatigue. Desmond and Matthews (1997) developed the following criteria for a countermeasure system. First, there must be a valid indication of fatigue. Next, there must be a stimulus upon detected weariness in order to restore performance. Balkin et al. (2011) defined three criteria for the ideal system: i) it can predict fatigue based on factors that produce it (i.e. sleep history), ii) it can measure fatigue and performance, and iii) it can intervene, restore and sustain performance and alertness.

Since fatigued drivers are especially at risk when demand is low, Desmond and Matthews (1997) think that a secondary task (i.e. monitoring an in-car guidance system) is beneficial whenever the primary task demand is low. However, since in-car guidance systems are now well established in modern cars, it seems that a secondary task should be designed differently. May and Baldwin (2009) define automation (to counteract on sleep-related fatigue) and interactive technology (i.e. a game as a secondary task to counteract task-related fatigue) as promising countermeasures for fatigue.

Gershon et al. (2009) actually found that a secondary, manual-dexterity task has a positive effect on subjective fatigue as well as alertness. They also found that non-professional and professional drivers already have different strategies to counteract cognitive fatigue (Gershon et al., 2011), such as listening to the radio, talking, opening the window and drinking coffee. Generally, it can be stated that providing variety from the monotonous driving task seems to have a positive effect on task-related cognitive fatigue. Schmidt et al. (2011) for instance found that communication has a positive effect on fatigue. Furthermore, chevrons, rumble strips and message signs also have a short-lived, positive effect on cognitive fatigue (Merat and Jamson, 2013). Next to this, haptic seat alerts decrease reaction time (Fitch et al., 2011). Since "vigilance is influenced by frequency and variety of stimulation" (Parasuraman et al., 1998), a fatigue countermeasure system should implement a palette of different stimuli in the vehicle interior in order to evoke driver vitalization.

### Current in-car systems against fatigue

Car manufacturers obviously have also been working on the development of systems to counteract driving fatigue. There are several systems in the industry that assess fatigue and suggest a break (Volvo, Ford, Daimler, BMW etc.). These systems usually monitor driving performance or time on task and encourage the driver to rest or actively alert the driver on impending errors. Thus, most of these systems focus on preventing accidents without being an actual countermeasure to task-related driver fatigue. Furthermore, Karrer-Gauß (2001) indicates that systems detecting and presenting fatigue level could be counterproductive and lead to drivers taking more risk.

When looking at other modes of travel, similarities can be found in terms of fatigue although the driving task is missing. This is for instance the case for airplane passengers, who experience physical fatigue from sitting as well as sleep-related fatigue. Airplane passengers are advised to do exercises approximately every hour, like tilting the feet, rotating ankles, stretching fingers etc. (KLM, 2013). Hitos et al. (2007) found that foot exercises against increased resistance positively enhanced blood volume flow and that other types of exercises moderated the negative effect.

There have also been successful attempts on counteracting on sleep-related fatigue in this field. Achim Leder (2012) used blue light in air plane interiors in order to decrease the production of sleeping hormones and evoke fitness. Another study focusing on medical personnel also found that blue light could be a countermeasure for fatigue especially at night (Harvard Medical School, 2006). However, providing car passengers with ambient, blue light at night is difficult since this will obstruct the driver's view. A possibility to evade this problem is to emit the blue light directly into the eye. Researchers have for instance been able to develop LED light-glasses with blue light to manipulate the circadian rhythm (Winslow, 2007).

## Micro-movements

A general hypothesis is that micro-movements could decrease discomfort from sitting. Since it is not possible to enable great postural change in a car due to the limitations of the driving task, this could be a promising measure for an automotive application. However, generally accepted recommendations on micro-movements are not yet established.

Graf (1995) stated that studies are needed on how often the sitting position should be changed and what the optimal range of changes is. Vergara and Page (2002) define a macro-movement as a distinctive change of posture every 5 to 6 minutes. Callaghan and McGill (2001) define a dynamic, multiple posture strategy during unsupported sitting as consisting of 3 postures over 2 hours. Helander et al. (2000) found that sensitivity of postural change results from the response from body tissues and joints. They established just noticeable differences in seat height, seat pan angle and backrest angle. Dunk and Callaghan (2010) found that micro-movements are a way to reduce discomfort from restlessness, body stiffness, lack of circulation or seat pressure and that fidgeting occurs every 40-50 seconds.

Several efforts have been made to develop dynamic seating with both passive as well as active micro-movements. Passive rotation of a pig cadaver spine results in an immediate increase of disc height at a rotation of less than 2 degrees (Van Deursen, 2001). Beach et al. (2003), however, tested a continuous passive motion device in an office chair, which resulted in no difference in EMG or locally perceived discomfort. Passive rotation in an office chair compared to no passive micro-movement for the same office tasks, resulted in significantly less spinal length in the static chair (Van Deursen, 2001). Nevertheless, a long term study on the effects of a similar passive motion device on low back pain found no advantage of the device (Lengsfeld et al. 2007).

Other than applying passive micro-movements, dynamic sitting could produce active micro-movements. Kingma and Van Dieen (2009-1) evaluated sitting on an exercise ball and concluded that, although it is questionable if there are benefits for the spine, there is more EMG variation in the back which could have positive effects. However, the disadvantages of having no support would probably outweigh the advantages of the sitting ball. Prolonged sitting on a dynamic, unstable surface does not significantly affect muscle activation, spine posture, spinal loads, or overall spine stability according to McGill et al. (2006). O'Sullivan (2012) also thinks that there is no evidence supporting the use of dynamic seating as a stand-alone approach for low back pain.

Nevertheless, Kingma and Van Dieën (2009-2) found that a vertically dynamic lumber support when driving a car results in a small reduction of vibration and a substantial reduction of low back EMG. In another study, Van Dieën (2001) found that working on a dynamic office chair results in an increase in body stature, but trunk kinematics and EMG were more affected by task. A chair with an unstable seat pan consisting of a pixel mat with an under layer of springs, results in significant lower heart rate as well as the maintenance of oxygen levels in the tissues surrounding the ischial tuberosities (Mahksous et al., 2008).

Next to reducing discomfort while seated, there is another relationship between micro-movements and fatigue. Rogé et al. (2001) found that during simulated driving subsidiary body movements increase when vigilance decreases. Micro-movements also seem to be a defense system against cognitive fatigue. The study shows that variation of non-specific activities is an indication of subject’s arousal and that self-centered gestures (movements of one or both hands towards the body) as well as postural adjustments have the purpose of reactivation. Takanishi et al. (2010) also found an increase of habitual behaviors (touching face, arms) related to a decrease in heart rate variation (which is a measurement of sympathetic nervous system activity). They state that distractive behaviors against monotony are an indication for decreasing performance. Thus, it seems that micro-movements are also a natural countermeasure against fatigue.

## Thermal Stimuli

In order to prevent fatigue caused by mental underload, the driver should be stimulated and the monotonic aspect of the trip should be diminished. Next to providing the car driver with a secondary manual task, offering physiological stimulation is an option. Table 1 shows an overview of literature mentioning this effect.

There are several studies indicating that local cooling leads to activation of the sympathetic nervous system. Activation of the sympathetic nervous system results into a (physiological) shift from a state of rest to a state of alertness: the sympathetic nervous system is responsible for priming the body for action (Van Halem, 2009) . Jansky et al. (2013) found that cooling of the lower legs with 12° water results in activation of the sympathetic nervous system within 3-10 minutes. Another study showed that immersion of the hand in cold (5°) water activates the SNS, measured by blood pressure and heart rate (LeBlanc et al., 1975). Koehn et al. (2012) found sympathetic activation by cooling head and neck with cold gel (4°). Furthermore, Sendowski et al. (1999) found that the SNS is activated when immersing the right hand or the left hand and right index finger in 5° water within 5 minutes, but not for immersion of only the right index finger. Ramautar et al. (2013) also found a cohesion between skin temperature fluctuations and objective vigilance. Another positive effect of alternating hot and cold temperatures is the increase of local blood flow (Cochrane, 2004) which could counteract on effects from physical fatigue resulting from static seating.

Since cooling body parts with 10° C water results in a shift of perceived thermal comfort from warm to cold (Tamura and An, 1993), however, it is challenging to develop automotive features with these extreme cooling effects without inducing overall discomfort. Additionally, there could be technical difficulties concerning the implementation of such low temperatures. Therefore, it is of interest to activate the sympathetic nervous system with as little difference in temperature as possible. Tham and Willem (2010) found that exposure to 20° room temperature already leads to a cooling sensation on the skin and to better accuracy versus a 24° waiting room in an office in the tropics. This small difference in temperature could be a promising notion for implementation of such features in cars.

Another possibility for activating the sympathetic nervous system is to use scent. According to Horii et al. (2013) aromatherapy can be used for alleviating stress as well as invigorating the body: the usage of grapefruit oil results in elevated sympathetic nerve activity.

Table 1: Effects of local cooling

| Author | Year | Body part | Temperature (° C) | Time (min.) | Effect |
|---|---|---|---|---|---|
| Jansky et al. | 2013 | Lower legs | 12 | 3-10 | SNS Activation |
| Koehn et al. | 2012 | Head and neck | 4 | Immediate effect | SNS Activation |
| LeBlanc et al. | 1975 | One hand | 5 | 2 | SNS Activation |
| Sendowski et al. | 1999 | Right hand/ left hand and right index finger | 5 | <5 | SNS Activation |
| Tamura and An | 1993 | 10 Different body regions independently | 10 | 30 | Thermal comfort shift from warm to cold |
| Tham and Willem | 2010 | Overall: environment | 20 | Continuous | Cooling sensation and better |

| | | |
|---|---|---|
| | effects over 240 | accuracy |

# MEASURABLE EFFECTS OF FATIGUE COUNTERMEASURES

There are three types of possible effects to a fatigue countermeasure: a physical, a mental and an emotional effect. Table 2 provides an overview of different methods of fatigue effect measurement used in experimental studies found during the literature review.

The physical effect is measurable with for instance heart rate (Backs et al., 2003; Mehler et al. 2008; Mehler et al., 2012; Reimer et al., 2011; Schmidt et al., 2011; Gershon et al., 2009; Patel et al., 2011; Yang et al., 2010) and skin conductance (Collet et al., 2003; Mehler et al., 2012). Another physiological effect of fatigue can be found in eye movements and pupillometry (Ahlstrom, 2013; DiStasi et al., 2012; Merat and Jamson, 2013; Schmidt et al., 2011; Yang et al., 2010). Furthermore, respiration frequency is used as a measure of sympathetic nervous system activity (Backs et al., 2003).

The mental effect consists of the cognitive processing of the driving task. This can be measured both objectively and subjectively. Objective measurements often used are EEG representing brain activity (Ahlstrom, 2013; Gillberg et al., 1996; Kar et al., 2010; Lal et al., 2003; Schmidt et al., 2011; Simon et al., 2011) and task performance such as reaction time and steering wheel movement (DiStasi et al., 2012; Gershon et al., 2009; Merat and Jamson, 2013; Nilsson et al., 1997; Sung et al., 2005; Thiffault and Bergeron, 2001; Ting et al., 2008 ). There are different questionnaires and scales evaluating workload and perceived fatigue as subjective measurements. For workload, a common tool is the NASA-TLX (Hart and Staveland, 1988) but there is also a Mental Workload Test (DiStasi et al., 2009). Two questionnaires often used to evaluate fatigue are the Karolinska Sleepiness Scale and the Stanford Sleepiness Scale.

The emotional effects can be measured subjectively. Concerning the topic of fatigue, it is of interest to evaluate the driver's state regarding boredom vs. arousal. This can be assessed with for instance Likert-scales attached to words describing emotions and user's state or tools as the Self Assessment Mannikin (SAM, Bradley and Lang, 1994) based on a model on pleasure, arousal and dominance or Emocards (Desmet et al., 2001).

Table 2: Methods of cognitive driver fatigue measurement

| **Author** | **Year** | **ECG** | **SCL** | **Respi-ration** | **Eye measure-ments** | **EEG** | **Perfor-mance** | **Subjective evaluation** |
|---|---|---|---|---|---|---|---|---|
| Ahlstrom et al. | 2013 | - | - | - | X | X | - | X |
| Backs et al. | 2003 | X | - | X | - | - | - | - |
| Collet et al. | 2003 | - | X | - | - | - | - | X |
| Desmond and Matthews | 1997 | - | - | - | - | - | - | X |
| DiStasi et al. | 2012 | - | - | - | X | - | - | X |
| Gershon et al. | 2009 | X | - | - | - | - | X | X |
| Gillberg et al. | 1996 | - | - | - | - | X | X | X |
| Kar et al. | 2010 | - | - | - | - | X | - | - |
| Lal et al. | 2003 | - | - | - | - | X | - | - |
| Liu and Wu | 2009 | - | - | - | - | - | - | X |
| Mehler et al. | 2008 | X | - | - | - | - | X | - |
| Mehler et al. | 2012 | X | X | - | X | - | X | - |
| Merat and Jamson | 2013 | - | - | - | X | - | X | - |
| Patel et al. | 2011 | X | - | - | - | - | - | - |
| Reimer et al. | 2011 | X | - | - | - | - | X | |
| Schmidt et al. | 2011 | X | - | - | X | - | - | X |
| Simon et al. | 2011 | - | - | - | - | X | - | - |
| Sung et al. | 2005 | - | - | - | - | - | X | X |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Thiffault and Bergeron | 2003 | - | - | - | - | - | X | - |
| Ting et al. | 2008 | - | - | - | - | - | X | X |
| Yang et al. | 2010 | X | - | - | X | - | - | - |

## CONCLUSION

Driver fatigue consists of physical and/or cognitive fatigue. Physical fatigue is related to perceptual-motor adjustments specific to the driving task (holding and operating the steering wheel, using the foot levers) and to discomfort caused by prolonged sitting. Possible countermeasures against physical fatigue are passive or active micro-movements and the stimulation of macro-movements. Cognitive fatigue can be subdivided in task-related and sleep-related fatigue. Sleep-related fatigue is considered intervention resistant by some researchers although there are studies that show a positive effect of blue light on this type of fatigue. Task-related fatigue is caused from task-overload or underload. In the case of task-overload, driver assist systems and automation provide a solution. In the case of task-underload a variety of stimulation is needed which can consist of a secondary task, haptics, thermal stimulation and scent. There are several objective and subjective measurements one can apply to evaluate a person's fatigue state.

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