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Psychophysiological responses to short-term cooling during a simulated monotonous driving task

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A B S T R A C T

For drivers on monotonous routes, cognitive fatigue causes discomfort and poses an important risk for traffic safety. Countermeasures against this type of fatigue are required and thermal stimulation is one intervention method. Surprisingly, there are hardly studies available to measure the effect of cooling while driving. Hence, to better understand the effect of short-term cooling on the perceived sleepiness of car drivers, a driving simulator study (n = 34) was conducted in which physiological and vehicular data during cooling and control conditions were compared. The evaluation of the study showed that cooling applied during a monotonous drive increased the alertness of the car driver. The sleepiness rankings were significantly lower for the cooling condition. Furthermore, the significant pupillary and electrodermal responses were physiological indicators for increased sympathetic activation. In addition, during cooling a better driving performance was observed. In conclusion, the study shows generally that cooling has a positive short-term effect on drivers' wakefulness; in detail, a cooling period of 3 min delivers best results.

1. Introduction

During long monotonous routes, drivers may find themselves in a state of low arousal due to lack of sensory stimulation. Low arousal describes an affective state in which individuals feel little activation, for example when being sleepy, bored or droopy (Russell, 1980). In the circumplex model of affect of Russell (1980) as well as in the mood theory of Watson and Tellegen (1985) emotions are viewed as combinations of the two basic orthogonal constructs valence and arousal. Later studies (Bradley and Lang, 1994; Thayer, 1989) report on semantic differential methods to subjectively measure valence and arousal states. These techniques become important when researching external factors – such as monotonous driving – on perceived arousal. Besides causing a deactivated state of the driver, the repetitive and predictable nature of monotonous drives turns the driving task also in an automatic process - a mode, also referred to as driving without awareness (DWA, Brown, 1994; Charlton and Starkey, 2011). The studies of Briest et al. (2006) and Karrer et al. (2005) proved that DWA and sleepiness are closely related. They found for example that DWA often precedes microsleep and that both DWA and sleepiness are indicated by changes in blink behavior. Another study supporting that monotonous routes foster the development of fatigue was done by Thiffault and Bergeron (2003), who found that monotonously simulated highway routes cause a vigilance decrement. That task underload on monotonous routes causes cognitive sleepiness is also reflected in several fatigue models (Lal and Craig, 2001; May and Baldwin, 2009; Van Veen et al., 2014) which distinguish different types of driver fatigue and their causes.

As a result of cognitive sleepiness, the driver grows uncomfortable during the trip. This not only inhibits pleasurable user experience but can also cause traffic risks due to lower levels of alertness of the driver. Tejero Gimeno et al. (2006) and Van Veen et al. (2014) list thermal stimulation as a possible countermeasure for cognitive sleepiness due to task underload in their reviews. The underlying principle for this is that outside of comfortable temperatures, the arousal of a human increases steadily (Parsons, 2003; Wyon, 1973). This means, that arousal is a function of ambient temperature, whereas the minimum arousal is at a comfortable temperature. It has also been shown that performance is a function of arousal (Hygge, 1992; Parsons, 2003), whereas there is an optimum level of arousal in which performance peaks. Higher or lower levels of arousal worsen the performance. The model of

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Hygge (1992) specifies the relationship between arousal and performance for easy and difficult tasks, in a way that the performance in easier tasks is generally higher than in difficult tasks, and that the optimum arousal level for easy tasks is higher than the required arousal for difficult tasks. From these theories, we draw that arousal and performance are influenced by the thermal environment, and that easy tasks require higher levels of arousal for best performance.

In practice, some studies can be identified investigating thermal stimulation of drivers. Surveys about countermeasures against fatigue report that "opening a window" or "turning on the AC" (air conditioning) are common practice among drivers (Anund et al., 2008; Gershon et al., 2011; Oron-Gilad and Shinar, 2000; Royal, 2003). Besides interview studies, a few controlled laboratory studies investigated the effect of cooling on the perceived sleepiness of car drivers with different outcomes. Wyon et al. (1996) compared the task performance in a driving study at a temperature of 21 °C and 27 °C and found a better performance at the lower temperature. In another example Van Veen (2016) investigated the effect of intermittent local hand cooling by a temperature difference of 5 °C to the ambient temperature on drowsiness and heart rate (HR) during simulated driving. While a significant increase of HR after 3 min of cooling was reported, indicating an activation of the sympathetic nervous system (SNS), the effect of short-term local cooling of the hands on perceived cognitive sleepiness was not significant. Another laboratory study was conducted by Landström et al. (1999) in which the effect of short-term room temperature drops from 28 °C to 18 °C on perceived sleep-related sleepiness and electroencephalogram (EEG) data was measured. Here they found a significant decrease in perceived sleepiness with cooling and EEG data proved an enhanced wakefulness. The study did not, however, include a driving task and focused on sleep-related fatigue. In a later field study, Landström et al. (2002) found that a temperature control system which cooled down the truck cabin temperature repeatedly by 8 °C to 10 °C with starting temperatures between 25 °C and 30 °C, increased the alertness in professional drivers. Since the truck drivers used the temperature control system during the night and mainly after long hours of driving, the study addressed sleep-related fatigue. Reyner and Horne (1998) found in a car simulator study, that 10 °C cold air neither had a significant effect on perceived sleepiness nor on EEG data after two and a half hours of driving. Their study also focused on drowsiness caused by sleep deprivation. Schwarz et al. (2012) worked with subjects which were not sleep-deprived and investigated the effect of intermittent 10 min-periods of opening the window for 2 cm at speeds of 120 km/h in a real-driving study. Subjective sleepiness and blink duration were not affected by this countermeasure.

Given these studies, it is surprising to see that the effect of thermal stimulation to relieve the strain of monotonous driving has hardly been explored. In order to gain knowledge on the effect of short-term cooling on cognitive fatigue in a controlled vehicle setting, a simulator study was performed. The aim of the study was to investigate a decrease in sleepiness caused by a task underload during a monotonous drive by means of cooling as well as exploring the effect of cooling on the emotions of the drivers using the semantic differential.

2. Experimental design

2.1. Apparatus

It was possible to use a street-legal car, changed only for experimental reasons. As the studies of Philip et al. (2005) and Hallvig et al. (2013) have shown, perceived sleepiness and physiological sleepiness is higher in simulated driving than in real driving for both sleep-deprived and non-sleep-deprived subjects due to lower levels of visuomotor stimulation. Since this study required to induce sleepiness due to monotony in non-sleep-deprived subjects, we decided to run a simulator study instead of a real-driving study which allowed also for reproducible traffic scenarios.

The cold air was provided by an external AC unit which was attached to the fresh air intake of the vehicle. Via remote control of the circulation flap and the interior fans of the vehicle, the cold air could be let in the cabin as required. Air at a temperature of 17 °C was used for the cooling condition because studies of Van Veen (2016) have shown a physiological effect at similar temperatures. In the control condition the cabin stayed at a thermo-neutral temperature (23 °C). After flipping the circulation flap, it took about 60 s before the measured temperature at the air inlets dropped from 23 °C to 17 °C, because the air channels of the car were warmed up to room temperature during the control period.

2.2. Participants

Fifty BMW Group employees recruited via a mailing list voluntarily participated in the study in February 2016. Of those, $n = 5$ participants were excluded from analysis by listwise deletion due to insufficient sleepiness level and $n = 9$ were excluded because of technical errors. Another $n = 2$ participants were not able to continue the study after the familiarization drive due to simulator sickness, resulting in a sample size of 34 participants for analysis. Study participants were 24 male and 10 female healthy subjects aged between 21 and 59 ($M = 31.8$, $SD = 11.2$). The participants kept their regular sleeping schedule, but were instructed to avoid tobacco or caffeinated beverages on the day of the study. The participants were examined at different times of the day. Seven participants took part from 8am to 10am, eight from 10am to 12pm, seven from 12pm to 2pm, eight from 2pm to 4pm and four from 4pm to 6pm. A Kruskal-Wallis test of the initial sleepiness ratings between the subjects of the five test times supports that the test time did not affect the sleepiness level ($H(4) = 1.93$, $p = 0.75$). The subjects were dressed in underwear, socks, shoes, pants and T-shirts in all thermal conditions of the experiment. The outside temperature during the period of the experiments ranged between −2 °C and 12 °C and the relative humidity ranged between 63% and 81%. Through the initial questionnaires, attachment and calibration of all sensors, the baseline recording of the electrocardiogram (ECG) and the familiarization drive, subjects could acclimate for 30 min to the thermal conditions of the simulator (23 °C and 35% relative humidity) before the start of the first test drive. The subjects did not know that cooling would be applied during the experiment.

2.3. Study design

The study employed a one-factor within-subject-design, in which all participants drove two monotonous highway routes—one with short-term cooling (COOL) at the end and one without (CONT) (Fig. 1). The order of the conditions was counterbalanced. The study began with one 5-min familiarization drive on a highway in which subjects could get used to the simulation environment. After the familiarization, the two test drives of 26 min followed. The duration of these drives was limited by the fact that total length of the experiment was limited to 90 min because the study took place during the participants' working hours. Both test drives were highway-routes with very little traffic in order to cause a monotonous task. Furthermore, subjects were instructed to drive no faster than 120 km/h.