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Mitigating passive fatigue during monotonous drives with thermal stimuli: Insights into the effect of different stimulation durations

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A R T I C L E I N F O

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A B S T R A C T

Driving on monotonous roads has been shown to cause passive fatigue as even non-sleep-deprived drivers suffer from the lack of stimuli. Consequently, alertness is reduced and the risk of accidents increases. To counteract this risk, measures need to be taken to mitigate driver fatigue. While in the past, some studies have been focused on the potential of thermal stimuli to reduce fatigue, their results seem inconclusive. Examining the study conditions in which the thermal stimuli were studied, it becomes obvious that the duration of the thermal stimulus strongly affects perceived fatigue. To better understand this relation, a driving simulator study (n = 33) was conducted investigating both a 2 min and a 4 min thermal stimulus (15 öC), where air was circulated on non-sleep-deprived drivers. For the 4 min stimulus, patterns of increased sympathetic activity (i.e. significant pupil dilatation and bradycardia) were recorded. Furthermore, participants subjectively rated fatigue significantly lower when the stimuli were applied, and preferred driving with the stimulus. The superior performance of the 4 min stimulus can be derived from a longer effect on the physiological data as well as even lower subjective fatigue ratings. Results also point to the limits of thermal stimulation: 6 min after the stimuli, the participants no longer feel an effect (based on subjective ratings). Future research on passive fatigue countermeasures should hence build on the identified effect of a 4 min cooling stimulus to increase physiological arousal and focus on the opportunities to increase effect duration.

1. Introduction

Driver fatigue can be subcategorized based on its causal factors, resulting in the differentiation of sleep-related and task-related fatigue. Passive fatigue, next to active fatigue, is a type of task-related fatigue and arises due to task underload (May and Baldwin, 2009). Task underload occurs e.g. when the driving task is monotonous, automated, or predictable, for example, on a monotonous highway with very little traffic (Tejero Gimeno et al., 2006). The lack of stimuli in these conditions impairs the driver's alertness (Larue et al., 2011). A study on the road monotony environment by Thiffault and Bergeron (2003) suggests "that fatigue is likely to manifest itself very early when driving in low demanding road environments". In practice, driver fatigue cannot be assigned to just one type of fatigue because it results from a mix of contextual factors. This study focuses on passive fatigue in order to reduce the accident risk resulting from monotonous driving.

To decrease fatigue due to monotony, several research efforts have been undertaken. Tejero Gimeno et al. (2006) and Van Veen et al. (2014) list secondary tasks and sensory stimulation as possible countermeasures based on literature reviews. The sensory stimuli can be of visual, auditory, olfactory, haptic or thermal nature. The following review focuses on the empirical effects of thermal stimuli.

There exists a set of studies indicating the effect of thermal stimuli on driver fatigue. According to interview studies (Gershon et al., 2011; Pylkkönen et al., 2015), drivers believed that "opening a window" or "turning on the air conditioning" are effective countermeasures.

Besides interview studies, Table 1 lists the few controlled driving studies, which investigated the effect of a thermal stimulus and which yielded different results.

A comparison of the five studies in Table 1 shows that the duration of the stimulus may be crucial regarding its effectiveness as a fatigue countermeasure. The study of Reyner and Horne (1998), which applied the longest lasting stimulus, is the only study listed that did not show any effects. Reyner and Horne (1998) detailed in their discussion, however, that effects were measured for several min in the beginning of cooling. All other studies of Table 1 focused on shorter stimulus durations between 2 min and 8 min and succeeded to demonstrate at least some physiological or subjective effects. The research of Van Veen

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Table 1
Summary of studies investigating the effect of thermal stimulation to mitigate driver fatigue.

Reference	Stimulus temperature	Stimulus duration	Body part	Sample	Effect of stimulus
Landström et al. (1999)	18 °C	2 min and 4 min	head	sleep-deprived	Significant increase in subjective wakefulness. Significant decrease in alpha activity (EEG).
Landström et al. (2002)	temperature drops of 8 °C–10 °C from 25 °C to 30 °C	2, 4, 6 and 8 min	not specified	sleep-deprived	Significant increase in subjective wakefulness.
Reyner and Horne (1998)	10 °C	2 h	face	sleep-deprived	Non-significant decrease in subjective sleepiness. Non-significant difference in EEG power (4–11 Hz).
Van Veen (2016)	temperature drops of 5 °C	4 min	hands	non-sleep-deprived	Non-significant decrease in subjective drowsiness. Significant increase in heart rate.
Schmidt et al. (2017)	17 °C	6 min	face	non-sleep-deprived	Significant decrease in subjective sleepiness and blink occurrences. Significant increase in pupil diameter and skin conductance. Significant reduction in lane deviations and steering jerkiness.

(2016) showed that hand cooling activated the SNS. In an earlier study, Van Veen et al. (2014) reviewed that an SNS activation occurred already after 2 min when the absolute hand cooling temperature was at 5 °C, and that even faster effects may be achieved by head and neck cooling. Schmidt et al. (2017) concluded that stimulus durations under 6 min may be preferable since participants indicated that they got used to the stimulus after a few min. This was also supported by their physiological data, which returned to control levels after 2–3 min (Schmidt et al., 2017).

From these insights, a simulator study with a monotonous driving task and different durations of thermal stimuli was conceived. On the one hand, this is because the missing subjective effects in Table 1 for the 2 h stimulus duration may be due to habituation effects and hence, long stimulus durations seem not suited to counteract fatigue. On the other hand, Van Veen et al. (2014) suggested that cold stimuli (e.g. 5 °C), need to be at least 2 min long to cause SNS activation. Therefore, it was hypothesized that an ideal stimulus lasts at least 2 min, but has to be shorter than 6 min. The current study compared the effects of two thermal stimuli (2 min and 4 min) that should be both long enough to invoke SNS effects, but are differently likely to be subject to habituation.

2. Materials and methods

2.1. Study design

The aim of this study was to gain further insights into the effects of different cooling durations to reduce passive fatigue. Passive fatigue of non-sleep-deprived participants was induced by means of a simulated monotonous driving task and thermal stimuli of different durations were applied.

The study employed a repeated-measures-design with the cooling duration as the independent variable. The factor was tested at three levels: control (CONT – no cooling), 2 min of facial cooling (COOL2) and 4 min of facial cooling (COOL4). The cooling durations were chosen based on the hypothesis that a stimulus has to be equal to or longer than 2 min and shorter than 6 min. Moreover, the 6 min stimulus has been investigated in a similar study (Schmidt et al., 2017). Taking these considerations into account, 2 and 4 min were chosen as stimulus durations, because these are equidistant in the given interval (2–6 min), acknowledging that 6 min have already been investigated. At all other times a thermo-neutral climate at 24 °C was maintained. To achieve cooling, the middle air vents were directed towards the face of the driver. The face was chosen as the target area in order to stimulate the trigeminal nerve, a mechanism that was described in the cold face test (Heath and Downey, 1990). In general, facial receptors respond to cold or wet stimulation of the area around the nose and eyes by stimulating both the sympathetic-vascular smooth muscle pathways and the cardiac-vagal pathway, causing what is known as the diving reflex (Collins et al., 1996; Heath and Downey, 1990). The present study made use of the activating effect of facial cooling on the SNS (Collins et al., 1996; LeBlanc et al., 1976). Since the airflow expanded in the cabin, the chill was not only perceptible on the face but also on the neck and upper chest.

To induce an early onset of passive fatigue, participants drove on monotonous roads for 15 min (Fig. 1). Based on the observations of Schmidt et al. (2016) on inducing passive fatigue by means of traffic scenarios, it is concluded that this period of monotonous driving in a simulator evokes sufficiently high fatigue ratings. After the fatigue induction period, one of the two cooling stimuli – COOL2 or COOL4 – was applied in a counterbalanced way. The stimulus was followed by a period of 6 min, in which participants kept driving without thermal stimulation. In this period, subjective and physiological fatigue were expected to return to pre-cooling levels. The reason for this shorter period before the second stimulus is the result from a previous study (Schmidt et al., 2017): Although thermal stimulation of the face increases physiological arousal and subjective alertness, drivers are still more fatigued after the stimulation compared to the start of the drive. Therefore, it was concluded, that it is not necessary to have the participants drive for another 15 min, as they did before the first stimulus. As there is no guarantee that the fatigue levels at the start of the two stimuli are equivalent, the order of COOL2 and COOL4 was counterbalanced. After this period, the respective alternative thermal stimulus was then applied, followed by another monotonous period of 6 min (Fig. 1). The total length of the drive summed up to 33 min and is referred to as COOL drive.

In order to generate corresponding control periods, the participants also completed another 33 min long drive with no stimuli (CONT). The order in which the participants completed the two drives was counterbalanced. After the first monotonous test drive the participants were tasked to shell and eat sunflower seeds for approximately 5 min – a dexterity mastication task which, according to the research of Gershon et al. (2009) activates drivers. This wakening effect was used between the two drives in an attempt to create a similar initial condition before the second monotonous drive.

The study began with one 5 min familiarization drive on a highway in which participants could get used to the simulation environment. All drives were highway-routes with very little traffic in order to cause a

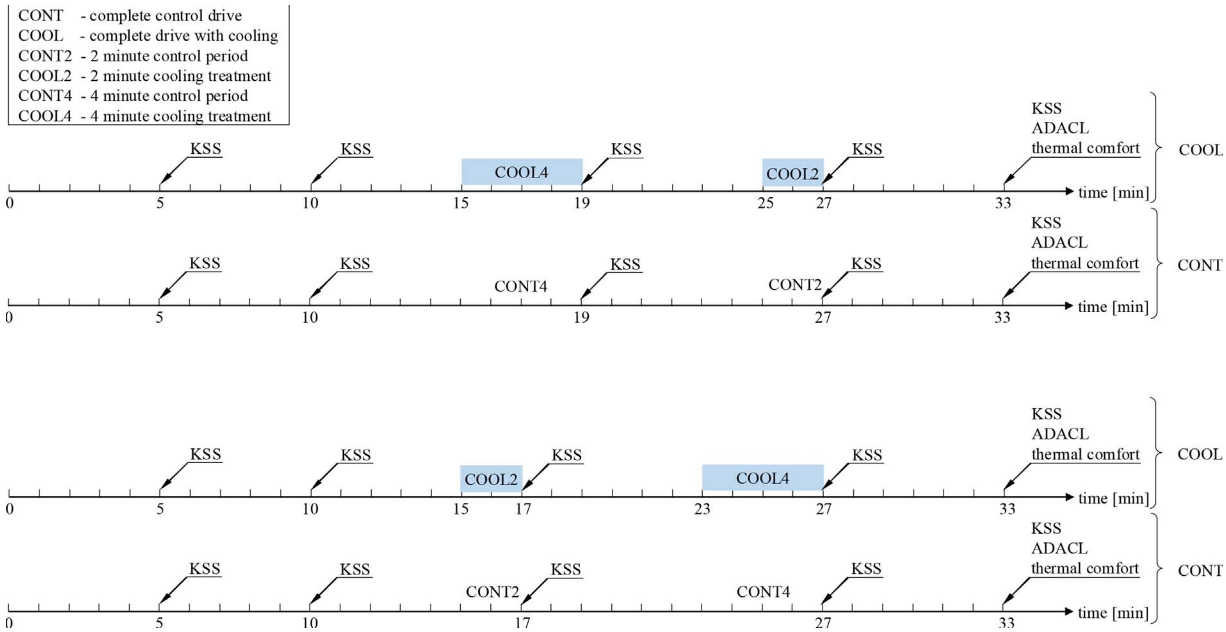

Fig. 1. Test drives with marked times of verbal assessment of fatigue, cooling durations and questionnaires.

monotonous task with low demand. Furthermore, participants were instructed to drive no faster than 90 km/h.

A street-legal battery electric vehicle was used as a test car and placed in a static simulator. The simulator method was chosen as previous studies have shown that both perceived and physiological sleepiness are higher in simulated driving than in real driving for sleep-deprived as well as non-sleep-deprived participants due to lower levels of visuomotor stimulation (Fors et al., 2016; Hallvig et al., 2013; Philip et al., 2005).

Via remote control of the air conditioning, cabin cooling could be controlled as required. Air at a temperature of 15 °C was used for the cooling condition because Schmidt et al. (2017) showed that effects were seen by a stimulus of 17 °C and increased airflow. In order to have a noticeable reduction in climate without the use of additional wind chill effects, the lower temperature of 15 °C was chosen. In the control condition, the cabin stayed at a thermo-neutral temperature (24 °C). In both conditions, the fan intensity stayed at 30%. After setting the temperature to 15 °C, it took about 60 s before the measured temperature at the air vents dropped from 24 °C to 15 °C. However, the change in temperature was clearly noticeable within the first seconds and therefore the cooling duration was measured starting from the start-time. After the cooling period, the rise of temperature from 15 °C back to 24 °C took only a few seconds. This is because warmer air, stored in an air channel, was led towards the air vents of the cabin by means of opening the channel flap instead of sending the cold air through a heater.

2.2. Participants

Thirty-five employees of the BMW Group recruited via a mailing list voluntarily participated in the study in October 2016, in Garching, Germany. Two participants could not continue the study after the familiarization drive because of simulator sickness. Therefore, the sample consisted of n = 33 healthy participants (28 male and 5 female) aged between 20 and 66 (M = 31.9, SD = 13.0). The participants kept their regular sleeping schedule and the average, self-reported sleep duration in the night before the study session was M = 6.8 h, SD = 0.9 h. Furthermore, they were instructed to avoid tobacco or caffeinated beverages on the day of the study, which all participants stated they adhered to. All tests took place from 8:00 am to 5:00 pm. After the 5 min familiarization drive the average KSS (Karolinska Sleepiness Scale) rating of the participants was M = 4.3, SD = 1.5, which is lies between ‘alert’ and ‘neither alert nor sleepy’. The participants were asked before the study to wear underwear, socks, shoes, pants and a short-sleeved T-shirt on the day of the experiment. In case the participants did not adhere to the instructions and wore T-shirts that differed from a regular cotton blend fabric or were long-sleeved, the experimenter provided T-shirts, which were available in different sizes. The outside temperature during the period of the experiments ranged between 9 °C and 19 °C. Through the initial questionnaires, attachment and calibration of all sensors, the baseline recording of the electrocardiogram (ECG) and the familiarization drive, participants could acclimate for half an hour to the thermal conditions of the simulator (24 °C and 35% relative humidity) before the start of the first test drive. The participants did not know that cooling would be applied during the experiment.

2.3. Dependent variables

At the beginning of the experiment, the participants signed a consent form and completed a questionnaire on demographic data, which included questions about the intake of caffeine, alcohol or cigarettes as well as the amount of sleep. Additionally, they provided an initial rating of their state using the KSS (Åkerstedt and Gillberg, 1990), translated into German by Niederl (2007). The KSS was originally developed to assess subjective sleepiness, which is caused by sleep deprivation (Åkerstedt and Gillberg, 1990) and has been suggested to correlate with EEG (electroencephalography) variables and behavioral sleepiness indicators (Kaida et al., 2006). In recent years, the KSS has also been used as a state measure in studies addressing passive fatigue caused by monotony, which is in contrast to its original application. In the studies of Schmidt et al. (2009, 2011), the KSS showed time-on-task effects with passive fatigue in non-sleep-deprived participants driving on real monotonous highways. Similarly, the KSS ratings also showed different fatigue levels caused by different non-driving related tasks during autonomous driving in the simulator study of Jarosch et al. (2017). In accordance with these studies, the KSS was used as a subjective measure in this study.

The KSS was also asked after the familiarization drive as well as verbally via a microphone-speaker system after the 5th and 10th min of the drives without stopping the drive as visualized in Fig. 1. Schmidt

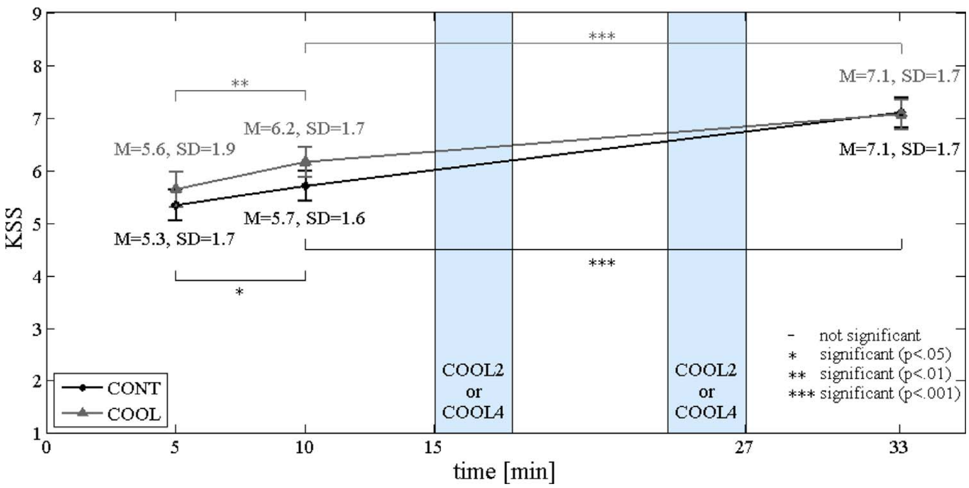

Fig. 2. Means and standard errors of the KSS ratings given over the course of the drives CONT and COOL.

et al. (2011) showed in their simulator study that fatigue can be verbally assessed every 5 min without a long-term activation of the driver. This is because the interactive communication only has an effect on the participants' vigilance level and physiological measures for a maximum of 2 min after assessment. Furthermore, the KSS was asked directly after the end of the COOL2 and COOL4 stimuli and at the corresponding points of time in the CONT drive (Fig. 1). To identify the sections in the CONT drive, which correspond to one of the cooling conditions, the abbreviations CONT2 and CONT4 are chosen and are marked in Fig. 1.

After each of the drives, the participants filled out several questionnaires including the KSS, the activation-deactivation adjective checklist (ADACL) (Thayer, 1989), German version by Imhof (1998), which was surveyed to measure the drivers' positive or negative activation, as well as the ASHRAE scale (ASHRAE, 1966) and the Bedford scale (Bedford, 1936) for evaluating thermal comfort. In case of the COOL drive, participants were asked to rate their thermal comfort they perceived during the coolest part of the drive.

After completion of the KSS, ADACL, ASHRAE and the Bedford scale, additional questions were asked in the case of the COOL drive to evaluate the wellness of the drivers. The central questions were the same as in the studies of Van Veen (2016) and Schmidt et al. (2017), with the goal of obtaining whether the drivers liked the cooling and whether they perceived that the cooling reduced fatigue. The participants could also describe their thoughts on the thermal stimulus and its effectiveness against passive fatigue in comment fields. After the participants completed both drives, they were asked which of the drives, CONT or COOL, they preferred.

A 3-channel-ECG for HR (heart rate) extraction as well as skin conductance were measured with medical sensors (g.tec, Austria) with a sampling frequency of 512 Hz. Gaze coordinates and pupil diameters of each eye were recorded at 60 Hz using a remote eye tracker (Tobii Pro X2-60, Sweden). The evidence of eye closures was extracted from a video signal using the software iMotions (Denmark).

2.4. Data analysis

Data analysis was performed in Matlab. Pupil diameters of both eyes were averaged. For the statistical analysis, all continuously recorded data and evaluated signals were averaged per min and participant. The analyses of skin conductance levels and eye closure evidences, while interesting for time-on-task effects, are not included in this article along with the gaze coordinate analysis, as those do not contribute to the assessment of the suitability of different stimulus durations. A significance level of 0.05 was used for all statistical tests, unless stated otherwise. The HR and pupil diameter data were normally distributed and it was hypothesized that HR would decrease and pupil diameter would increase with cooling as previous study results have shown (Schmidt et al., 2017). Therefore, one-sided t-tests were used for statistical analyses of the cooling effect.

Furthermore, an ANOVA was conducted for testing of interaction effects of the variables 'condition' (CONT, COOL2 and COOL4) and 'time' (before, during and after the stimulus) on HR and pupil diameter. For the factor level 'during', the continuously recorded data were averaged for the entire stimulus duration (which was 4 min in the case of COOL4 and 2 min in the case of COOL2). For the other levels 'before' and 'after', the data was averaged over 4 min. The signal window directly before the stimulus start was used (for 'before'), as well as the window from 1 min after stimulus end to 5 min after stimulus end (for 'after'). The 'after'-window was chosen not to be directly after the stimulus, since the KSS assessment causes effects in the physiological data.

The evaluation of the results of the normally distributed KSS ratings and the not normally distributed ADACL was done using one-sided t-tests and Wilcoxon tests, respectively, as it was hypothesized that the constructs 'energy' and 'tension' increase whereas 'tiredness', 'calmness' and the KSS ratings decrease in the COOL condition.

3. Results

3.1. Time-on-task effect

Participants perceived increasing fatigue levels over the course of the drive. Fig. 2 shows the average KSS ratings of all participants after min 5, 10 and 33 for the CONT and COOL drives. There were no significant differences between the two conditions at any of the times as two sided t-tests show ($t(32) = -1.1$, $p = 0.30$ at 5 min; $t(32) = -1.6$, $p = 0.12$ at 10 min; $t(32) = 0.1$, $p = 0.93$ at 33 min). The insignificant difference of KSS ratings at the end of the drives indicates that the second cooling has not resulted in a lasting effect. This supports the hypothesis that 6 min after the stimulus, fatigue continues. Subjective fatigue increased significantly from min 5–10 in both drives (CONT: $t(32) = -2.7$, $p = 0.01$; COOL: $t(32) = -3.2$, $p = 0.004$) and from min 10–33 (CONT: $t(32) = -4.2$, $p < 0.001$; COOL: $t(32) = -4.6$, $p < 0.001$), as confirmed by the two-sided t-tests.

3.2. Effect of stimulus durations

The recorded ECG and eye data provided insights into changes in physiological arousal. ECG data of $n_{ECG} = 31$ participants were of usable quality and were included in the analysis. Pupil tracking was successful with $n_{pupil} = 30$ participants.

The ANOVA of HR yielded that neither the factors 'condition' nor 'time' had a significant main effect. There was, however, a significant interaction effect ($F(4, 120) = 3.22$, $p = 0.01$) of the 'condition' and

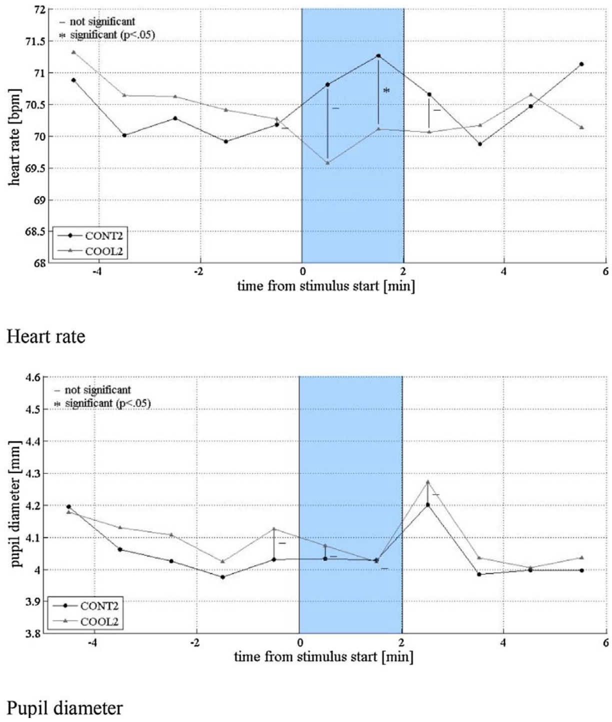

Fig. 3. Physiological measures a) heart rate and b) pupil diameter recorded before, during and after the application of the 2 min thermal stimulus (COOL2) as well as the corresponding section in the control drive.

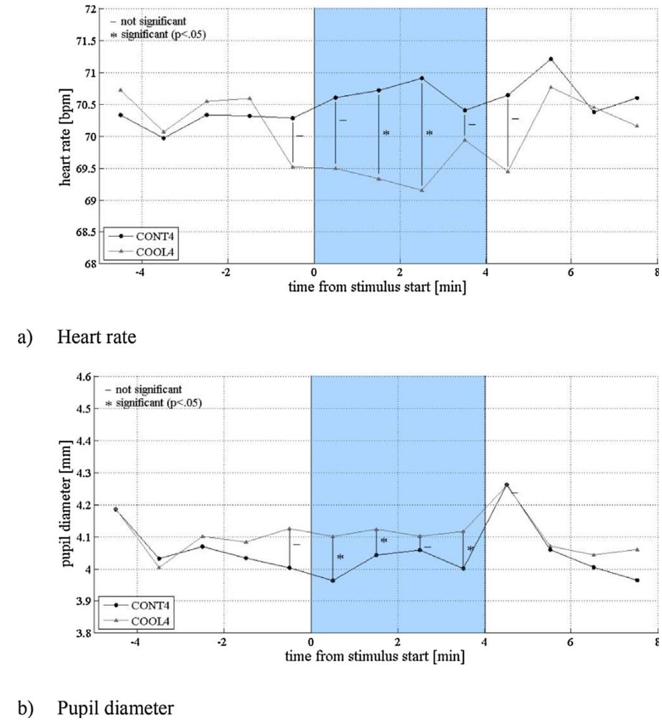

Fig. 4. Physiological measures a) heart rate and b) pupil diameter recorded before, during and after the application of the 4 min thermal stimulus (COOL4) as well as the corresponding section in the control drive.

‘time’ on HR. Post-hoc tests showed that the interaction occurred, when comparing the HR during and after cooling in the CONT conditions with COOL4. There was a main effect of ‘time’ on the pupil diameter ($F(2, 58) = 11.8$, $p < 0.01$), but no interaction effects of ‘condition’ and ‘time’ ($F(4, 116) = 1.07$, $p = 0.37$).

The minute wise comparisons revealed that the stimulus, when observed on a higher resolution, partly affected the physiological measures.

First, during the COOL2 stimulus, the HR in the CONT2 condition was higher. In the first cooling min this difference was only a trend ($t(30) = 1.6$, $p = 0.059$), but in the second min, HR was significantly different ($t(30) = 1.8$, $p = 0.04$) between the conditions (Fig. 3a). There were no significant differences in HR in the min before and after the cooling. There were also no differences in pupil diameter (Fig. 3b) between the CONT2 and COOL2 condition in the min before, during and after the cooling. The peaks of the pupil diameters after the 2 min cooling stimulus were due to the verbal KSS assessment given at this time (Fig. 3b).

Second, the results of the COOL4 stimulus are presented. As hypothesized, HR decreased during the stimulus (Fig. 4a). As in the COOL2 evaluation, the HR decrease became significant for the second min of cooling ($t(30) = 1.8$, $p = 0.04$). It decreased even further in the third cooling min ($t(30) = 2.8$, $p = 0.005$), but returned to pre-cooling level in the fourth cooling min (Fig. 4a). The pupil diameter behaved as hypothesized and significantly increased for the first ($t(29) = -2.3$, $p = 0.02$), second ($t(29) = -1.8$, $p = 0.04$) and fourth ($t(29) = -2.3$, $p = 0.01$) cooling min (Fig. 4b). Again, there were no differences between the conditions in the min before and after cooling in both HR and pupil diameter.

The subjective assessments also indicate that drivers felt more alert after the COOL2 and COOL4 treatments. A comparison of the KSS ratings given after COOL2 ($M = 6.2$, $SD = 2.1$) and at the respective times of the control drive, CONT2 ($M = 6.7$, $SD = 1.4$), shows that KSS ratings were significantly lower after the COOL2 condition ($t(32) = -1.9$, $p = 0.03$) (Fig. 5a). An even larger difference ($t(32) = -2.2$, $p = 0.02$) was found between the KSS ratings given after COOL4 ($M = 6.1$, $SD = 1.9$) and those after the CONT4 assessments ($M = 6.7$, $SD = 1.6$) (Fig. 5b). When comparing the KSS ratings after the COOL2 and the COOL4 stimuli with each other, no significant difference between these two was found ($t(32) = 0.5$, $p = 0.64$).

As explained earlier, the participants were tasked to perform a dexterity mastication task between the drives, which was expected to reduce the passive fatigue that developed over the course of the first drive. A comparison of the KSS ratings provided after 5 min of driving in the first ($M = 5.2$, $SD = 1.9$) and second ($M = 5.8$, $SD = 1.7$) drive shows that the difference was non-significant ($t(32) = -1.4$, $p = 0.18$). Also the differences of the ratings provided after 10 min ($t(32) = -1.2$, $p = 0.25$) and 33 min ($t(32) = 0.1$, $p = 0.95$) were non-significant between the first and the second drive.

The evaluation of the results of the ADACL showed that none of the hypothesis were confirmed, as all changes were non-significant. However, there was a trend for increased ‘energy’ ($Z = -1.35$, $p = 0.09$) and decreased ‘tiredness’ ($Z = 1.34$, $p = 0.09$) after the COOL drive.

An evaluation of the questions regarding the participants’ impressions of the cooling reveals that 85% of the drivers liked the cooling, and 100% believed that cooling reduced fatigue. After experiencing both the CONT and COOL drive, 91% of the drivers preferred a monotonous drive with short-term cooling. This means that some of the people who did not like the cooling would still prefer to drive with intermittent short-term cooling because of its activating effect.

The mean thermal sensation according to the ASHRAE Scale was ‘slightly warm’ ($M = 1.27$, $SD = 0.84$) in the CONT condition and ‘slightly cool’ ($M = -1.03$, $SD = 1.05$) in the COOL condition.

4. Discussion

It was the aim of the study to investigate different cold stimulus durations with respect to their effect on reducing passive fatigue during

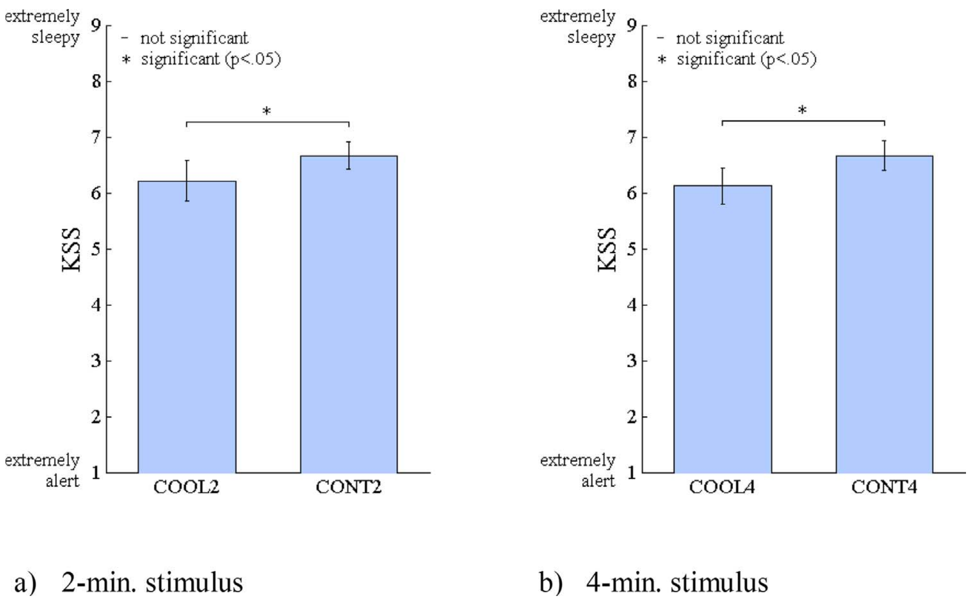

Fig. 5. Means and standard error of the KSS ratings given directly after a) COOL2 and CONT2 and b) COOL4 and CONT4.

monotonous driving. Based on the statistical test results of the KSS rating given after the COOL2 and the COOL4 condition compared to the rating at the corresponding times in the CONT condition, it can be concluded that both stimuli reduced subjective fatigue (Fig. 5). The COOL2 stimulus significantly decreased KSS ratings, whereas the physiological measures were hardly affected. The absolute mean difference of the KSS ratings between COOL2 and CONT2, however, was relatively low: 0.5 on a scale from 1 to 9. Similarly, the COOL4 stimulus caused reduced subjective fatigue as well as increased physiological arousal. In terms of the subjective ratings, the KSS ratings were significantly decreased, and again, the absolute mean difference of 0.6 on the KSS scale is low (Fig. 5).

The results of the subjective ratings in this study aligns with the related studies in Table 1, which used facial or head cooling that lasted no longer than 8 min. The results of this study are in contrast to the findings on subjective ratings of Van Veen (2016) and Reyner and Horne (1998). The study of Van Veen (2016) yielded non-significant differences in subjective ratings, which may be due to absence of trigeminal nerve stimulation, because only the hands were cooled. The non-significant changes in subjective ratings produced by the 2 h stimulus of Reyner and Horne (1998) are likely due to habituation effects.

The observed increase in pupil diameter (Fig. 4b) was very likely a response of an SNS activation and could be interpreted as increased physiological arousal. This could be the reason why the drivers' alertness consequently increased in the short term. In addition to pupil dilatation, the facial cooling stimulus initiated a decrease in HR, which was assumed to be a vagal reflex that was probably caused by the parasympathetic activation during trigeminal nerve stimulation, which in turn has been shown to be initiated by facial receptors (Collins et al., 1996; LeBlanc et al., 1976). The reduction in HR due to facial cooling in this study is in contrast to the observations on hand cooling of Van Veen (2016) which caused an acceleration of HR. It has been shown, though, that hand and face cooling evoke different reactions in HR, as LeBlanc et al. (1975) showed with their comparative study on cold hand tests and cold face tests. The HR decrease in this study was not significantly lower in the first min of cooling, but only for the second (and third in COOL4) cooling min (Figs. 3a and Fig. 4a). This is contrary to Schmidt et al. (2017), in which an immediate decrease was measured. The reason for this could be related to the fan intensity. In this study, the fan intensity was fixed and it took about 60 s before the temperature at the air vents dropped from 24 °C to 15 °C, therefore, the stimulus was not reflected in the HR response in the first min.

Comparing both stimuli, the absolute decrease in subjective fatigue was larger for the COOL4 condition. Besides this result of subjective evaluation, the analysis of physiological data supports a larger effect of the COOL4 stimulus, as can be seen by the continued effects on HR and pupil diameters measured in the COOL4 stimulus event. Thus, the COOL4 stimulus proved to be more effective than the COOL2 stimulus. As studies with longer thermal stimuli have shown (2 h by Reyner and Horne (1998) and 6 min by Schmidt et al. (2017)), these longer-lasting stimuli did not result in physiological effects. This suggests that thermal stimuli cease to be effective after some period of time. The current study results suggest the time at which that happens is after approximately 3 min.

In contrast to the KSS ratings provided directly after the stimulus, the ADACL failed to show a continued activation of the driver. This questionnaire was asked 6 min after the second cooling stimulus ended. This delay between the stimulus and the ADACL questionnaire likely caused the non-significant decrease of the construct 'tiredness' in the ADACL, because the cooling does not have a continued wakening effect.

The responses of the drivers about their feelings towards the cooling and their preference on how to conduct a monotonous drive shows that the majority of people liked the cooling and that most participants would prefer to drive in a monotonous setting with intermittent cooling. This increased perception of wellness was surprising as earlier studies (Schmidt et al., 2017; Van Veen, 2016) have shown very different results with almost half the study participants disliking the cooling. The difference in the outcomes of these investigations is surmised to be due to the fanning intensity because in this study, there was no increase in the airflow towards the body (i.e., keeping the fan intensity at 30%).

Summarizing, the COOL4 stimulus reduced subjective fatigue and increased physiological activation in the short term and most of the drivers liked the stimulus. Still, many more research steps are required to use this effect for successful fatigue management.

The first limitation of this study is that the participants did not start the experimental drives with an equal initial KSS rating and the amount of sleep in the night before the experiment varied. Furthermore, some of the participants drove during their circadian afternoon dip, so that a minor influence of sleep-related fatigue cannot be ruled out. Another shortcoming of this study is that the KSS was used as a subjective measure of the driver's state. This is because the KSS was developed to measure sleepiness, but its use as a fatigue indicator has not been validated. Furthermore, the participants might have been alerted to the experimental question of the study after they were asked to rank fatigue directly after they felt the cold stimulus. The lack of safety-relevant driving maneuvers in the simulated highway-drive is an important shortcoming in the study design because no reaction times effects of the stimulus can be retrieved from the driving data.

Another limitation is that the study was conducted in a driving simulator in which the visuomotor stimulation is low compared to real driving. Investigating the effects in real driving conditions would be particularly interesting because the effect of thermal stimulation could be decreased, as it may be less noticeable in combination with the visuomotor stimulation. Conversely, the effect of thermal stimulation may be increased since the drivers might be less fatigued because of the additional stimuli in real driving and the cooling might relieve the strain from drivers more efficiently.

Finally, both COOL2 and COOL4 condition were tested within one drive instead of separate drives. Separate drives would have more equivalent starting conditions before cooling was applied, at the expense of a longer total duration of the study, because another 15 min pre-cooling, and 6 min post-cooling time would have been required for a third drive. The fact that there was no significant difference between the KSS ratings after 33 min of the CONT drive and the COOL drive indicates that passive fatigue redevelops within 6 min through monotonous drives. This observation also means that the effect of the thermal stimulus does not have a longer lasting impact on fatigue. The finding that arousal lasts for less than 6 min after a cooling stimulus, contributes to our understanding that the countermeasure is very short-lived.

5. Conclusions

With regard to successful fatigue management, the use of thermal stimulation has several limitations. First, it is unknown whether the proposed countermeasure is suited to combat also types of fatigue other than passive fatigue. Second, the stimulus only has a short-lived effect on the drivers' wakefulness. These observations are crucial because driver fatigue constitutes itself as a result of several factors, such as the circadian rhythm, the duration of the drive, monotony of the drive and physical fatigue due to prolonged sitting and therefore the impairment of the driver can only in rare cases be solely attributed to passive fatigue. Therefore, further research is needed to examine whether thermal stimuli affect fatigue that occurs for other reasons than monotony.

Besides, the short-lived effect of thermal stimulation poses a problem because the stimulus would have to be applied repeatedly to cause a prolonged activation of the driver and it is uncertain that the stimulus would still have an effect after a certain amount of repetitions. Literature on passive fatigue and monotony shows that the repetitive nature of a drive can foster the development of passive fatigue which can be a drawback of repeated cooling unless the stimulus is varied in some way. Investigating the effects of, for example, tactile, olfactory, auditory and visual stimuli or secondary tasks per se, might open up new possibilities to design a fatigue management system.

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