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Driving performance in cold, warm, and thermoneutral environments

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Abstract

Driving performance deteriorates at high ambient temperatures. Less is known about the effect of low ambient temperatures and the role of subjective aspects like thermal comfort and having control over the ambient temperature. Therefore, an experiment was constructed in which 50 subjects performed a road-tracking task in a cold (5°C), a thermoneutral (20°C) or a warm (35°C) climate. All subjects had a heater/blower (H/B) which generated a fixed amount of heat/wind that could either be controlled or not controlled.

In the cold climate, averaged leg skin temperature dropped to 18.5°C and head skin temperature to 24.9°C; the thermal comfort was rated between ‘cold’ and ‘very cold’. In the warm climate, averaged leg skin temperature rose to 36.6°C and head skin temperature to 30.8°C; the thermal comfort was rated as ‘hot’. Driving performance in the ambient temperature extremes decreased 16% in the cold environment and 13% in the warm situation.

Having control over the local head temperature by adjusting a H/B affected neither thermal comfort nor driving performance. In agreement with the literature on priming effects, subjects who started with the no-control condition performed much better in all driving tasks because they were primed to focus on the driving task as such, rather than the complex combination of temperature controls and driving task.

It can be concluded that a thermoneutral temperature in a car enhances driving performance and may thus positively affect safety. Using manual climatic controls in hot or cold cars may interfere with the driving task.

Keywords: Driving performance; Cold; Heat

1. Introduction

Ambient temperature is an important factor in the occurrence of traffic accidents. Zlatoper (1991) investigated the influence of ten factors on traffic accident incidence and observed that temperature rated third, before factors like alcohol abuse or the use of safety belts. Fortunately, air conditioning in cars is becoming increasingly common and it is often claimed that air conditioning in cars improves thermal comfort, driving performance and thus safety at high ambient temperatures. The beneficial effect of lowering high ambient temperature on driving performance is clearly shown by Mackie and O’Hanlon (1977) and Wyon et al. (1996), but no physiological measures were taken to assess the impact of the heat stress on the human body. Moreover, the effect of low ambient temperature on driving performance is hardly looked at, and the relation between thermal comfort and driving performance is also almost absent in the literature (see, for instance, Parker’s (1995) review of over 3000 studies on temperature effects). This is unfortunate as the practical relevance of the topic is beyond dispute. Therefore, an experiment was conducted in which driving performance as well as thermal comfort were measured during a driving task in cold, warm, and thermoneutral conditions.

Like in cars, the subjects had a heater/blower (H/B) aimed at the face to modify the local climate. A H/B in a car modifies the local climate *and* provides the subject with control over the situation. Both effects may increase thermal comfort or vigilance, which in turn improves the driving behaviour and performance. An example of the impact of having control on driving

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behaviour and performance can be found in the decreased safety of car driving after the introduction of safety belts (Janssen, 1994). To investigate both effects separately, subjects in the three temperature conditions performed the same driving tasks in a session in which they could control the H/B and a session without control.

The order of these two sessions was considered crucial because of the unconscious effect of prior context on the interpretation and retrieval of information and related behavior, known as the priming effect (e.g., Fiske and Taylor, 1991). If the context of H/B control is offered first, subjects will come to define the entire situation of both sessions as one in which the tasks of temperature control and driving control are both important. If, in contrast, the no-control context is offered first, subjects will be primed to view driving control task as the single most important feature of both sessions. As a consequence, subjects may well perform better throughout when they start with a no-control priming than when they start with a control priming. We therefore decided to include the order of the control and no-control sessions as a between-subjects factor in the experimental design.

In summary, the experiment seeks to yield information about the relation between temperatures, thermal comfort and driving performance. If a relation exists, we try to identify whether the thermal environment itself or the having temperature control is the main determinant.

It is hypothesized that the thermal comfort and driving performance will be optimal during thermoneutrality and that the extra task of controlling the local head temperature will decrease the vigilance and thus decrease driving performance. Furthermore, it is hypothesized that subjects starting with the no-control condition show better performance since they focus on the driving task (priming effect). Fig. 1 summarizes the conceptual framework under investigation.

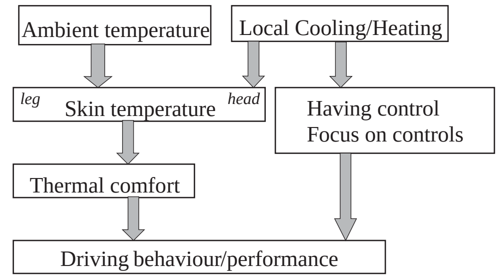

Fig. 1. Possible relations between temperatures, comfort and driving behaviour.

Table 1
Characteristics of the groups participating in the study

Variable	Cold (5°C)	Thermoneutral (20°C)	Warm (35°C)
Number of subjects	18	14	18
Male/female	9/9	7/7	9/9
Age	22 ± 3	22 ± 5	25 ± 6
Weight	70 ± 11	65 ± 11	70 ± 12
Stature	176 ± 7	177 ± 10	175 ± 9

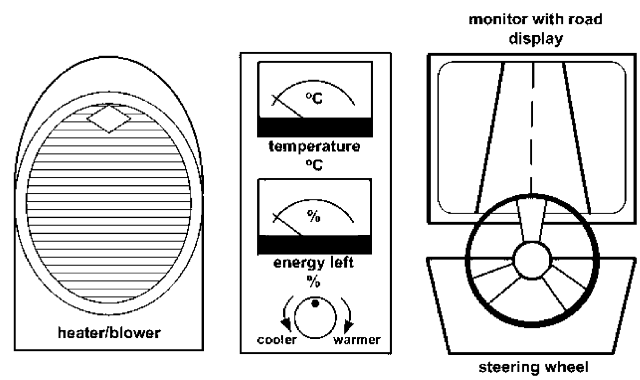

Fig. 2. Schematic view of the experimental set-up with the steering wheel in front of the monitor and the control box and H/B next to it.

2. Materials and methods

2.1. Subjects

Fifty subjects participated in the experiment. The subjects were randomly assigned to three groups: a group that performs the driving task in the cold condition (5°C, 50% relative humidity), a group in the thermoneutral condition (20°C, 50% relative humidity), and a group in the warm condition (35°C, 50% humidity).

The characteristics of the groups, abbreviated with C, N and W, respectively, are shown in Table 1. The groups did not differ significantly in age, weight and stature. The gender was equally distributed in the C, N and W groups. The local ethical committee of TNO Human Factors approved the experiment.

2.2. Methods

The experiment was carried out in a climatic chamber, which was subdivided into six compartments. The temperature accuracy of the chamber was about 1°C and the relative humidity was accurate within about 3%. The subjects were dressed in underwear, socks, shoes, jeans and a T-shirt for all thermal conditions. After entering the climatic chamber, the subject sat quietly for 30 min to be accustomed to the thermal environment. The subjects could not see each other.

Each subject had a steering wheel in front with a monitor standing behind it (Fig. 2). The monitor displayed the information about the experiment, the road for the driving task and the questionnaire. The subjects were asked to drive on the right lane of the road by turning the steering wheel. The driving task lasted two times 7 min of which two times 5 min were processed; the last and first minute were deleted to eliminate start and end effects. During the driving period, side wind was increased with 0.125 m/s every 15 s to make the task more complex (Brouwer et al., 1991). Side wind was visualized as a deviation from the road to the side. The position on the road (relative to the middle of the right lane) and the standard deviation of the lateral position (SDLP) were sampled 30 times per second and stored to disk every 15 s. The SDLP is an important indicator of driving performance, although Parasuraman (1986) warns that this relatively simple task may benefit from an increase in arousal, while a complex driving task may not.

A custom made H/B was positioned left of the monitor aiming at the face of the subject. The H/B was steered by a central computer. The heater and blower were both activated in the cold. In the warm condition, only the blower was on. In the thermoneutral condition, the blower was only slightly activated (to keep the H/B switched-on part of the manipulation constant) and the heater was off. The H/B had a control for the heater on the box (Fig. 2) and a separate control for the blower. One indicator showed the current power delivered by the H/B on a temperature scale and another indicator showed the total energy used. When the subjects were allowed to control the local head climate, the information of the controls was processed by the computer and the temperature of the heater and the blowing speed were adjusted accordingly. The number of times that the controls were adjusted was counted.

Each subject came to the laboratory for two consecutive test sessions. In one session the subjects were told that they could control the temperature by means of the H/B (the control or CT session) and in the other session they could not (NC—no control session). Twenty-five subjects started with the CT session and 25 subjects started with the NC session. The total amount of (hot) air supplied to the face was identical for the CT and NC session. This means that if subjects in the CT session opted for a quick warm-up in the cold condition, the last part of the experiment had to be relatively cool. The driving task was interrupted each 3 min to allow the subject to modify the blower speed and heater.

Apart from the temperature and control manipulations, the CT and NC sessions were identical in that they consisted of several tasks, as shown in Table 2. The H/B was started after the test drive and operated for 30 min.

To estimate the thermal strain, the subjects were instrumented with a continuous heart rate measurement system (Polar Vantage NV, Fin-90440 Kempele, Finland), a copper/constantane thermocouple (Tempcontrol T-T-28M, Voorburg, The Netherlands) located on the lower leg and an identical thermocouple located on the forehead. The skin temperatures were written down after each session.

Table 2
Tasks in each session

Task	Duration (min)
Read the instructions on the monitor	5
Test drive	1
First driving task	7
Filling in the questionnaire on the screen	± 10
Second driving task	7
Filling in the questionnaire on the screen	± 7

Thermal comfort was rated on a scale ranging from –4 (very cold) to +4 (very hot) according to ISO 10551 (1995). The questionnaire also included a list of feelings about driving performance and risk behaviour. The latter results will not be reported here.

As briefly mentioned in the introductory section, the control can be split into driving control and temperature control. Three questions out of 22 were related to driving control (how well could you control the driving task, how well could you control the steering wheel, how well was everything under control) and two questions were related to thermal control (how well could you control ambient temperature, how well could you control body temperature). These questions were significantly correlated and grouped in the items driving control and temperature control. The questions were scored on a 7 point scale (1 = full control; 7 = no control) after the first and second experiment. The mean values were calculated for statistical processing.

2.3. Statistics

Dependent variables are thermal comfort, number of control adjustments, heart rate and skin temperatures (head and leg) and driving performance.

The predictive factors of primary interest are ambient temperature (C, N or W) and control (CT or NC).

To examine the occurrence of priming effects, differences between the order of the control and no-control sessions was investigated (CT-NC or NC-CT). Also, gender effects were included in the analysis.

Statistical analysis was performed using analysis of variance with ambient temperature, gender, and order effect as main independent factors (Statsoft, 2000). The temperature by gender interaction effect was also calculated. Control (CT or NC) and session orders were included in the analysis as covariates. A Tukey post-hoc analysis was performed when the anova yielded significant results.

3. Results

3.1. Effect of ambient temperature

Table 3 shows the values of the variables for the three ambient temperature conditions.

The leg temperature was much closer to the ambient temperature than the forehead temperature. The heart rate was not different between C and N, but considerably higher in the W condition. As might be expected, thermal comfort ranged from 'very cold' (−3.4) to 'neutral' (−0.1) to 'very hot' (3.1). Also in agreement with the manipulations, the heater controls were mainly used in the cold conditions and the blower controls in the warm condition. The performance during thermoneutrality was 14% better than in the ambient temperature extremes. A post-hoc analysis revealed that C and N differed significantly, but W and N did not. The position on the road did not depend on ambient temperature.

3.2. Effect of control

The temperature control feeling was 3.9 ± 1.0 for the CT condition and 5.0 ± 0.9 for the NC condition. This means that the actual possibility of having control was also experienced that way.

In the control condition, the blower was used 11 times on average and only 7 times in the non-control condition. Surprisingly, the heater was used equally often in the NC and CT condition (about 15 times on average). There were no other differences in the selected variables between the NC and CT condition. Also, there was no significant interaction between the temperature conditions (C, N, W) and control (CT, NC).

The heater and blower were operated more often in the first session than in the second session (14 versus 9 for the heater and 12 versus 6 for the blower).

The subjects who started with the NC condition performed much better than the subjects who started with the CT condition: 97 (± 28) cm for the NC-CT order versus 128 (± 25) cm for the CT-NC order (Fig. 3). The position on the road did not differ between the two starting conditions: -73 ± 46 and -57 ± 30 cm for the CT-NC and NC-CT order, respectively. The subjects who started the NC condition adjusted the heater more often (15 times) then the subjects who started with the CT condition (9 times). Table 4 gives an overview of the effect of control and order of the control sessions on performance and H/B operation.

Fig. 3 shows the driving performance or SDLP for the repeated driving task (see Table 2). The performance of the second driving task was worse than the first. This may be related to the effect of cold and heat on the

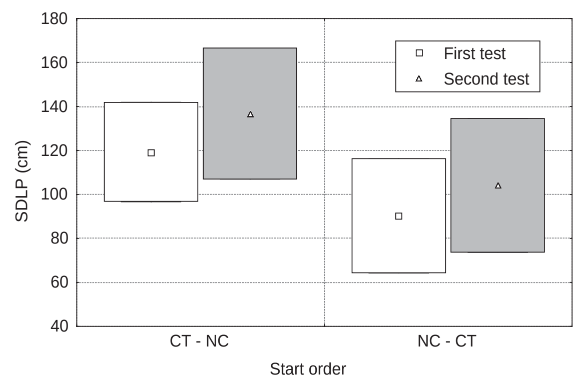

Fig. 3. Effect of the order in which the NC/CT conditions were imposed on SDLP (in cm) of the first and second driving task. The symbols denote the mean and the length of the box denotes the standard deviation.

Table 3
Leg skin temperature (°C), head skin temperature (°C), heart rate (beats/min), thermal comfort (arb. units—4 is very hot; −4 is very cold), number of times the heater and blower was adjusted, driving and temperature control (1 = full control, 7 = no control), driving position (in cm from the middle of the right line) and standard deviation of the lateral position (SDLP in cm) for the three ambient temperature conditions (C = cold, N = thermoneutral, W = warm)

Variable	C (5°C)		N (20°C)		W (35°C)		
	Mean	s.d.	Mean	s.d.	Mean	s.d.	Sign.
Leg temperature (°C)	18.5	3.8	28.1	1.3	36.6	0.7	*
Head temperature (°C)	24.9	1.2	28.4	1.9	30.8	3.0	*
Heart rate (b.p.m.)	76	16	70	13	98	10	*
Thermal comfort	−3.4	1.0	0.0	1.2	3.1	1.3	*
Heater adjustm.	24	20	9	11	2	4	*
Blower adjustm.	2	6	5	12	21	20	*
Driving control	4.8	1.0	4.3	1.0	4.8	1.0	NS
Temperature control	4.6	1.0	4.0	1.2	4.8	0.9	*
Driving position (cm)	−68	38	−60	28	−65	48	NS
SDLP (cm)	118	32	102	29	115	31	*

The asterisk denotes significant differences.

Table 4
Effect of control (CT) and no-control (NC) and of the order effect of the control and no-control sessions (CT-NC and NC-CT) on driving performance (standard deviation of the lateral position in cm) and the number of times the heater or blower was adjusted

Session	CT-NC			NC-CT		
	Performance	Blower adjustments	Heater adjustments	Performance	Blower adjustments	Heater adjustments
CT	128±23	13.9±19.7	10.6±11.8	97±30	7.6±14.3	12.5±15.1
NC	127±29	4.7±8.6	6.4±11.3	98±27	8.9±16.6	17.8±23.0

human body, illustrated by the continuing drop in skin temperature in the cold, and increase in skin temperature in the heat.

4. Discussion

4.1. Effect of ambient temperature

The results show that the selected extreme ambient temperatures have a profound impact on human skin temperature. The body core temperature is expected to show only a minor increase in the cold and warm conditions since the time span of 30 min is too short. The expected core temperature increase in the cold is mainly due to the increased metabolism due to shivering (Daanen and Van de Linde, 1992). The core temperature was not measured in order to minimize the discomfort of other factors than climate.

In order to maintain core temperature in the cold, the blood vessels in the skin vasoconstrict. The human extremities are particularly affected, as can be seen by the low temperature of the lower leg. The skin temperature of the human head is less affected.

The heart rate in the warm condition is 23 beats/min higher than in the cold or thermoneutral condition. This is consistent with the literature and attributed to a direct link between peripheral thermal receptors and the nerves controlling the heart via the hypothalamus (Houdas and Ring, 1982). Also, vasodilatation in the skin, a direct and indirect effect of the surrounding heat, expands the blood volume in the skin and the heart has to pump more frequently to comply with this. Consequently, the skin temperature is relatively high. The skin temperature of the forehead is lower than that of the lower leg, due to the evaporative cooling of the sweat on the forehead.

Skin and core temperature contribute in equal amount to thermal comfort ratings (Frank et al., 1999). Therefore, it is not surprising that thermal comfort differed strongly between the three thermal conditions C, N and W. This is in line with the framework shown in Fig. 1. The feeling of thermal control over the situation was better in the thermoneutral session.

Human driving performance, quantified by the SDLP, differed significantly between the three conditions, even though a between subjects design was used and large interindividual differences in task performance existed. A within subject design is more sensitive and may have yielded results that are more pronounced. The decrease in performance in the heat is also observed by Mackie and O'Hanlon (1977), who compared a 37°C to a 24°C ambient temperature and found a performance decrease due to heat of 35%. Wyon et al. (1996) found that 50% more signals were missed when driving in 27°C as compared to 21°C. In our study, the performance decrease in the heat was 13% (see Table 3). It was interesting to note that no differences existed in the experienced control over the car between the three thermal conditions. Wyon et al. (1996) attribute the performance decrease to an increased arousal leading to a decreased ability to handle the information in a complex driving task. Since our driving task was less complex, this may explain why less performance decrease as the study of Wyon et al. (1996) was found in our study.

The driving performance decrease in the cold is less well studied. It is known that the manual dexterity decreases considerably, but mainly for fine dexterity tasks (Lockhart et al., 1975). The driving tasks did not involve fine dexterity tasks, so it is more likely that psychological factors dominate in the explanation of the observed performance decrease of 16%. However, some subjects were shivering, which may have interfered with the driving task.

Ellis (1982) and Enander (1987) found that performance time on a vigilance task improved in moderate cold, but that the number of errors increased. Two hypotheses were offered as an explanation. The first hypothesis was a higher arousal level and the second was a higher distraction level in cold. Both hypotheses were compatible with their data and with the data of our experiment. Further research is needed to elucidate the underlying mechanism of performance decrease in the cold.

4.2. Effect of control

In the heat, the subjects used the blower controls more often in the CT condition than in NC, as expected. In the cold, however, the heater buttons were adjusted in similar amounts in CT and NC. Maybe the subjects used each opportunity in the cold to move and thus to generate heat.

Having control over the H/B did not affect any physiological measurement nor the driving performance. However, the questionnaire results show that they experienced the ability to control the thermal environment. The generated heat by the heater can be no confounder, since the total energy for the NC and CT was kept identical.

We observed that the driving performance of subjects who started with the NC condition was 32% better than the subject who started with the CT condition (100(128−97)/97—Table 4). There were no differences in gender, age or anthropometric dimensions that could explain this difference. Also, there were no differences in heart rate, skin temperatures and thermal comfort between the two groups. A highly plausible explanation is that this reflects a priming effect of the experimental context that was offered first (for more on priming effects, see Fiske and Taylor, 1991). Subjects who start with the NC condition know and remember that the controls do not change the thermal environment and behave on the basis of the conviction that the driving task is the only task that counts. In the subsequent CT condition they maintain focussed on the driving task and a good driving performance. The subjects starting with the CT condition face a more complex definition of the task situation in which temperature control may be as salient as or even more salient than driving control. They may start thinking about the strategy they will follow and try to perceive the thermal sensations induced by operating the controls. This will have drawn attention away from the driving task and will have decreased the performance. However, the heater was adjusted more often in the NC-CT condition than in the CT-NC condition. This means that the performance was better and the heater was used more often in the NC-CT condition. Possibly, the subjects quickly turned the control in the first NC condition without focussing on the effect on their body, while in the first CT condition, the subjects turned the controls less often to experience the effect of the H/B. This means that the number of times a control is operated may not be a good estimator for the attention paid to it.

In conclusion:

- Leg and head skin temperature and thermal comfort were drastically altered when ambient temperature was set to 5°C or 35°C;
- Driving performance in the ambient temperature extremes was worse than at 20°C;
- Having control over the local head temperature by adjusting a heater/blower did not affect thermal comfort or driving performance;
- However, the subjects who were primed to exclusively focus on the driving task rather than the combined task of temperature and driving controls performed much better in all driving tasks.

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