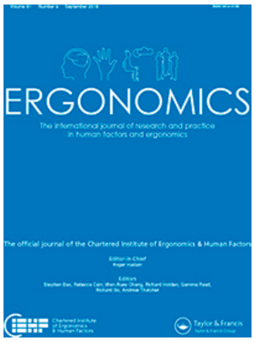

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Effects of moderate heat stress on driver vigilance in a moving vehicle

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A total of 83 drivers, 51 males and 32 females, aged 25–65, were recruited to drive an apparently unmodified passenger car for 1 h over at least four laps of a predetermined route on public roads, which included seven sets of traffic lights and sections limited to 50, 70, 90 and 110 km/h. They were randomly assigned to one of two thermal conditions (21 or 27°C), and drove only during the hours of daylight. A computer initiated unprepared signals to which drivers would normally be alert. Drivers responded by pressing a foot-switch and reporting verbally. Signals were selected at random from 21 possible signals, and were presented for up to 3 min, with a random delay of 30–180 s after each response or failure to respond. The negative effect of heat stress on vigilance was statistically significant. At 27°C, the overall proportion of missed signals was 50% higher and response times were 22% longer than they were at 21°C. These effects of heat were significant and proportionally greater in the second half-hour, for subjects <40 years and for speeds below 60 km/h (i.e. in city traffic). The latter finding suggests that heat may have increased arousal, and there was some indication of a redistribution of attention away from the most peripheral signals at the higher temperature. Overt driving errors were observed significantly more often at 27°C than at 21°C for women only.

1. Introduction

Recent advances in the assessment of vehicle climate (Wyon *et al.* 1989) make it possible to state that drivers are exposed to a considerably higher degree of thermal asymmetry than is encountered in comparable stationary workplaces. With the exception of vehicles without air-conditioning in hot weather, it is usually possible for drivers to adjust the average temperature of the compartment until their total rate of heat loss is equal to their metabolic heat production, but this is usually achieved by subjecting some parts of the body to excessive heat loss, while other parts remain too hot. In order to protect the coldest parts of the body, it is very common for drivers to select an average temperature several degrees higher than would be required in an indoor environment. This preferred bias is observed even in cold weather, although it is greater in air-conditioned vehicles in hot weather. It can only be reduced by improving the

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distribution of cooling power over the body surface of the driver, but as this is expensive, often involving a considerably more complex ventilation system, it would be necessary to justify the added cost by showing that a small upward bias of compartment temperature has an adverse effect on driver performance and therefore on road safety.

It has been shown that the very high levels of heat stress that occur in vehicles without air-conditioning in summer-time in Arizona (which causes profuse sweating and a marked and progressive increase in pulse rate) lead to reduced rear-view mirror vigilance and an increase in driving errors classed as 'moving violations' in the American penal code (Mackie *et al.* 1974). Very high levels of heat stress have been shown in the laboratory to reduce peripheral awareness by increasing arousal (Bursill 1958), but similar effects have never been demonstrated at the very moderate levels of heat stress of interest in the present connection, i.e. below the sweating threshold (Hockey 1986). Moderate heat stress has often been shown to have adverse effects on mental performance in a stationary laboratory setting (Wyon 1993), and this is believed to be due to a decrease in arousal, giving rise to a reduced ability to concentrate, and reduced work rates. This reduction would not necessarily take place if the subject was driving a vehicle: modern theoretical analyses of the role of arousal in modifying performance emphasize effort as a co-ordinating principle between arousal and activation (Sanders 1981), and drivers must be assumed to be prepared to exert effort to maintain an adequate level of arousal in the interests of their own safety. Even if the direction of heat effects on arousal in the driving context were known, it would not be possible to predict with any certainty the resulting effects on vigilance: in a recent review of theoretical approaches to vigilance, Parasuraman (1986) states that an increase in arousal is usually beneficial for vigilance in very simple vigilance tasks, but warns against applying theory derived from laboratory studies to such complex tasks as driving.

The present experiment was designed to investigate whether moderate heat stress will reduce driver vigilance for unexpected signals. As the signals used in the experiment may all occur occasionally in the driving context, the approach may be considered as sampling part of a subject's attentional field while driving by means of an embedded secondary task, i.e. one that is not artificially added.

2. Method

2.1. *Task setting*

In a simulated driving task it is possible for subjects to grossly distort their distribution of attention in order to improve their performance on some aspect of the task that is normally unimportant, with no penalty in terms of accident risk. In a moving vehicle, in real traffic, drivers must assign attentional priorities realistically in the interests of their own safety. It was therefore decided to carry out the experiment in an apparently unmodified vehicle, at normal speeds and in actual traffic.

2.2. *Cabin temperature*

The independent variable was the compartment temperature in the car, which was set to either 21° or 27°C and remained constant throughout each exposure.

2.3. *Vigilance as part of the driving task*

The dependent variable was the assignment of attention to essential sources of information of varying degrees of priority within the driving task. The primary aspect of the driving task, namely proceeding at normal speeds over a predetermined route without causing danger, was not examined systematically, except that overt errors in route-finding and violations of the traffic code were discreetly noted as they occurred.

2.4. *Subjects*

Subjects who had held a driving licence for at least 5 years were recruited in such a way as to give approximately the same age distribution within each gender. The age of each subject was recorded. Local bus, taxi, police and military drivers were recruited initially, then their relatives and friends, and the staff of a research institute. The need for subjects was not advertised, but to facilitate recruitment, they were paid SEK 200 (US $25) for their participation. Subjects were randomly assigned to the two experimental conditions. This was achieved by alternating the set temperature between consecutive subjects, while allowing subjects to choose their own time of participation, so that assignment of subject to condition depended only on whether an odd or even number of subjects had participated up to that time. Alternation throughout each day ensured that diurnal effects on performance were balanced between conditions, and that any unusual visibility, weather and traffic conditions would affect both the conditions equally on average. None of the subjects was aware that the air temperature in the vehicle was the subject of the study, or that other subjects experienced different thermal conditions. They were induced to believe that the experiment concerned the ergonomic design of the instruments in the vehicle, which were of the latest type, and unfamiliar to most of the subjects.

2.5. *Vehicle*

The test vehicle was a 1989 Volvo 760 estate with a 4-speed automatic gearbox. It was equipped with a standard Volvo ECC air-conditioning unit (Electronic Climate Control), which was operated in the 'automatic' mode, in which the fan speed and the air distribution are optimized by a microprocessor to maintain thermal conditions equivalent to the pre-set air temperature, which in this experiment was selected by the experimenter and was not affected by the usual temperature setting control. The effects of changing external temperature and solar load on the driver's heat balance are automatically corrected by automatic alterations in the compartment air temperature. A foot switch of the type once used for dipping headlights was mounted on the floor for left foot operation by the driver. The foot switch was used to start and stop a tape-recorder connected to a microphone in front of the driver and to simultaneously signal the subject's response to the computer. This is described in § 2.7.

2.6. *Signals*

Although the vehicle appeared to the subjects to be unmodified, it was possible for an on-board computer to alter the indication of most of the instruments, to light warning lamps, to operate some of the controls, and to simulate emergency conditions either aurally or visually, as follows.

Speedometer:	20 km/h bias up or down, 3 s gradual onset.
Engine RPM:	800 rpm bias up or down, 3 s gradual onset.
Analogue clock:	Alteration by one minute per second forwards or backwards.
Water temperature:	Bias to red warning area on dial.
Fuel:	Slow decrease from over half-full to empty in 90 s.
Warning lamps:	Brake failure, parking brake, oil pressure low.

Generator:	All warning lamps on as if fan-belt broken or generator out of operation for some other reason.
Indicators:	Panel lamp flashes as if left or right direction indicator was operating. External indicators are not operated.
Wipers:	Windscreen wipers operate spontaneously at low speed.
Signal horn:	Horn sounds briefly and spontaneously.
Noise rear:	Barely audible vibration near left rear wheel, frequency increasing with road speed.
Engine noise:	Loud and clearly audible vibration from engine compartment just in front of driver, frequency increasing with engine speed.
Police behind:	Blue flashing lights visible in only one of three rear-view mirrors, operated as three separate signals. Lights are attached externally by magnet to the rear wings, and inside the rear window. Subjects are instructed to monitor all three continuously.

2.7. *Responses*

The sole response required of the driver was to depress the foot switch, await an audible tone, report verbally at leisure while holding down the foot switch, and then release it. In order to eliminate the possibility that the subject might spot the true signal as it was removed, and alter the verbal report accordingly, signals were not removed until the foot switch had been released, stopping the tape recorder. As content analysis of the verbal report was carried out off-line, the signal was removed whether or not the verbal report identified the current signal correctly. Only one signal was in operation at any time, although subjects were not aware of this limitation, nor of which signals could occur.

2.8. *Instructions*

Subjects were first asked to sit in the driving seat and to adjust the driving mirrors correctly, using the electric remote control for the two external rear-viewing mirrors. The three blue lights were pointed out to them, and subjects were instructed to monitor each of them separately in the three mirrors and to report at once if one of them began to flash. The floor switch and the microphone (mounted above the windscreen on the passenger side, pointing towards the driver's face) were pointed out and their use for verbal reporting was explained. Subjects were instructed to also report 'any other occurrences deviating from normal operation'. A single example of such an occurrence was given, namely that the dashboard clock might stop. This was not in fact one of the signals used in the experiment. The subject was shown the digital clock on the car radio and instructed to use that as a reference if it was suspected that the analogue clock on the instrument panel was wrong. This was to be immediately reported, and it was to be re-set. The use of the forward/backward re-set buttons was explained. No other examples of the 21 possible signals were given.

Subjects were instructed to proceed in 'Drive', without using kickdown or manual over-ride, and not to use the left foot for braking. They were informed that they themselves were responsible for obeying the rules of the road, and for driving safely. They were to place first priority on driving normally, and to perform the vigilance task only as a secondary task, with much lower priority.

2.9. *Modified display*
It had been found in preliminary studies that the standard warning lamps were so bright that subjects did not fail to notice them at once. A strip of blue plastic film was therefore fixed over the row of warning lamps on the instrument panel. Their perceived colour was unchanged, but their intensity and contrast were reduced. The film transmitted 68% of incident light The measured contrast of the warning lamps was reduced from 35% to 9%, making them much more difficult to perceive with peripheral vision, although clearly perceptible when the subject looked directly at the instrument panel.

2.10. *Signal sequence*
The computer was programmed to select any one of the 21 signals at random, with equal probability, and to impose a delay of random length, from 30 to 180 s, after each response or failure to respond. Signals were removed after 180 s if no response had been made. The same signal could occur again without restriction. Signals were never initiated while the vehicle was standing still, but were not removed if the vehicle stopped.

2.11. *Experimenter*
A female experimenter was always present in the left rear seat during the test drive. Driving errors such as failing to stop at an intersection with a mandatory stop sign, failing to stop at a red traffic light, or failing to start driving at green, were discreetly noted by the experimenter.

2.12. *Driving conditions*
Subjects drove round the predetermined route at least four times, and for at least 60 min, whichever took longer. The route was partly through the centre of Gävle, Sweden (population 60 000), including seven sets of traffic lights, and partly on the E4 motorway bypass and its approach roads, a total of 14·4 km. Each subject therefore drove at least 57·6 km over roads with which they were familiar. On the first circuit, the experimenter gave all necessary instructions for following the route. On the second circuit, instructions were given only if this was clearly necessary, which was noted. On the third and fourth circuit, no instructions were given unless the subject made a wrong turning, which was duly noted. The computer forewarned the experimenter when indicated speed was reduced by 20 km/h. True road speed was then indicated continuously on the computer screen, which was not visible to the subject. If the subject began to respond to the incorrect indication by increasing speed above the mandatory speed limit, the experimenter was prepared to instruct the driver at once to press the response pedal and restore correct speed indication. The necessity for this intervention did not occur. The experiment took place during the hours of daylight in May 1990. Subjects were not permitted to open windows or the sunroof.

3. Results

3.1. *Subjects*
Fifty-one male and 32 female subjects aged from 25 to 65 years took part in the experiment. A total of 54% of all subjects were below 40 years of age, and the effects of heat were therefore examined separately for the groups '<40 years' and '40 + years'. Chi-square = 0·08 on 2 df for a gender difference in age distribution. This value does not approach significance, so any differences in thermal effects between

gender groups will be unaffected by whatever age effects may also be found to exist, and vice versa.

3.2. *Driver vigilance, statistical analysis*

The response time (RT), from 0–180 s, for each correctly identified signal or 'hit', was recorded each time a signal was presented, with an accuracy of 0·01 s. As signals were selected in random sequence, no signal was in fact presented to all 83 subjects, and some subjects were presented more than once with the same signal. In all 1666 signals were presented during the experiment, of which 81% were detected, while 16% of them were missed even though they had been presented for the full 180 s. The remaining 3% were missed because they had been removed after the subject made a response that was later classed as other than a correct identification. In addition to the 1352 correct responses, a further 151 (11%) 'false positive' responses were made, of which only 34 resulted in the removal of a signal before it had been detected.

3.3. *Dependent variables*

The proportion of signals detected and the average RT for all correctly identified signals, regardless of which combination of signals had been presented, was calculated for each subject and used as the dependent variable in separate distribution-free Mann-Whitney U-test analyses (Siegel 1956) for an effect of temperature on these measures of vigilance. The experimental hypothesis in the analyses was that drivers would be less vigilant at the higher compartment temperature.

A pseudo-RT taking the value 0–360 s and denoted R(360), was derived for all 1666 occasions on which a signal had been presented, i.e. combining hit and miss data. When the signal had been correctly identified, R(360) was set equal to the measured RT ($0 < RT < 180$). For the 3% of signals that had been incorrectly identified, 180 s were added to the time for which the signal had been presented up to the incorrect response, and R(360) was set equal to this augmented value. When no response had been made within 180 s, and the signal had therefore been cancelled, R(360) was set equal to 360 s. The magnitude of R(360) has no meaning: it is an intermediate stage in a numerical procedure that rank-orders hits before misses, short response times before long, occasions when a signal was ignored for a short time before occasions when it was ignored for a longer time, and all of the preceding outcomes before occasions when the signal was missed altogether. R(360) was analysed for each signal separately, regardless of which subjects were involved, using the Mann-Whitney U-test. This analysis takes account only of the rank order of the different possible outcomes, as set out above. RT for hits was analysed separately for each signal, regardless of which subjects were involved. The distribution of RT values is positively skewed, and the analysis was therefore carried out using Student's t-test on the log-transform of RT. Finally, hits and misses were analysed as alternative categories of outcome, using a chi-square test for independence, for each signal separately. Where expected cell frequencies were < 5, the Fisher exact probability test (Siegel 1956) was used instead.

3.4. *Driver vigilance, percentage detection (all signals)*

Table 1 shows, for each analysis, the number of subjects and the mean rank for each thermal condition, together with $Z(0, 1)$ and the Mann-Whitney U-value from which it is derived. $Z(0, 1)$ is normally distributed with unit variance, and is shown as negative when vigilance was reduced by raised temperature. The p-values are for a 2-tail test. The proportion of signals detected, calculated for each subject regardless of which

Table 1. Mann-Whitney U-test of percentage detection (all signals).

	21°C		27°C				
	Rank†	N	Rank†	N	M-WU	$Z(0,1)$	2-tail p
Overall							
0–60 min	48·5	42	35·4	41	589·0	−2·48	<0·013
Time on task							
0–30 min	46·0	42	37·9	41	692·0	−1·54	ns
30–60 min	49·9	42	33·9	41	527·5	−3·04	<0·002
City (<60 km.h)/Higher speeds							
Speed <60 km/h	50·2	42	33·6	41	518·0	−3·12	<0·002
Higher speeds	44·0	42	40·0	41	777·5	−0·76	ns
Speed <60 km/h: time on task							
0–30 min	45·6	42	38·3	41	709·5	−1·38	ns
30–60 min	49·6	41	34·2	41	540·0	−2·92	<0·004
Higher speeds: time on task							
0–30 min	43·7	42	40·3	41	791·0	−0·64	ns
30–60 min	44·8	42	39·1	41	742·5	−1·08	ns
Age of driver							
Driver <40 years	25·9	25	19·4	20	177·0	−1·67	ns
Older drivers	23·4	17	16·4	21	112·5	−1·94	<0·052
Driver <40 years: time on task							
0–30 min	23·9	25	21·9	20	227·5	−0·51	ns
30–60 min	27·1	25	17·9	20	147·5	−2·34	<0·019
Older drivers: time on task							
0–30 min	22·7	17	16·9	21	124·0	−1·60	ns
30–60 min	23·1	17	16·6	21	117·5	−1·79	ns
Gender							
Male Drivers	29·5	28	21·7	23	224·0	−1·86	ns
Female drivers	18·9	14	14·6	18	92·5	−1·27	ns
Male drivers: time on task							
0–30 min	27·5	28	24·1	23	279·0	−0·81	ns
30–60 min	30·6	28	20·4	23	193·0	−2·44	<0·015
Female drivers: time on task							
0–30 min	18·5	14	14·9	18	97·5	−1·08	ns
30–60 min	19·3	14	14·3	18	87·0	−1·48	ns

$p > 0{\cdot}06$ marked 'ns'.
† Mean ranks assigned in each condition.
Negative Z indicates negative effect of heat (fewer signals detected).
NB: Mean *ranks*, not mean values, are shown for each condition, as the calculation is based on rank-ordered data.

signals were presented, was significantly lower at 27°C than at 21°C ($p < 0{\cdot}02$) during the whole exposure. The effect was highly significant ($p < 0{\cdot}002$) in the second half-hour, but did not reach significance in the first half-hour. Thermal effects on percentage detection were highly significant ($p < 0{\cdot}002$) in city traffic (i.e. at speeds below 60 km/h), and in the second half-hour in city traffic ($p < 0{\cdot}004$), but not in the first half-hour or at higher speeds. The effect of temperature approached significance ($p < 0{\cdot}052$) for older drivers in the whole exposure, and was significant ($p < 0{\cdot}02$) for younger drivers in the second half-hour. Although thermal effects on percentage detection in the whole hour did not reach significance for either gender considered

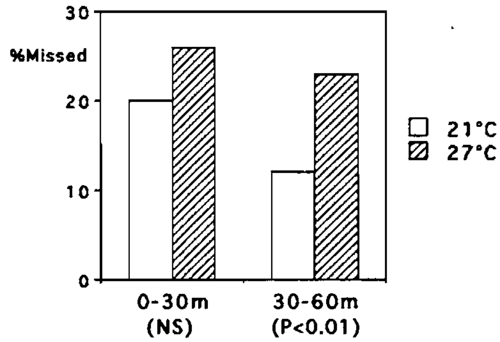

Figure 1. Percentage missed signals by time on task.

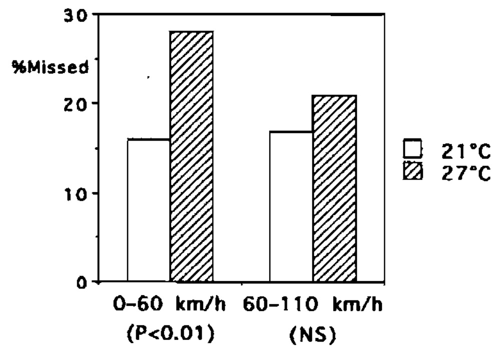

Figure 2. Percentage missed signals by road speed.

separately, male drivers detected significantly fewer signals at the higher temperature in the second half-hour ($p < 0{\cdot}02$), while female drivers did not. Thus thermal effects on vigilance were particularly marked in the second half-hour, in city traffic, for younger drivers, and for male subjects. The magnitude of these effects is illustrated in figures 1 and 2. In the second half-hour, subjects missed 92% more signals at 27° than at 21°C, and in city traffic, subjects missed 75% more signals in the raised temperature condition. Overall, subjects missed 16% of all signals at 21°C and 24% at 27°C, i.e. they missed 50% more signals in the raised temperature condition.

3.5. *Driver vigilance, average response time (all signals)*

Table 2 shows that average response times, calculated across all signals presented to each subject, were significantly increased at 27°C ($p < 0{\cdot}05$) during the whole exposure. The effect was not significant in the first half-hour, but was significant in the second ($p < 0{\cdot}05$). Thermal effects did not reach significance when the data were analysed separately for city traffic (speeds < 60 km/h) and for higher speeds. They were significant ($p < 0{\cdot}05$) for younger drivers (aged < 40 years) but not for older drivers, and particularly ($p < 0{\cdot}02$) for younger drivers in the first half-hour. Thermal effects did not reach significance for either gender considered separately. Responses tended to be slower in the second half-hour in general, but in the first half-hour for younger subjects. The magnitude of these effects is illustrated in figures 3 and 4. In the second half-hour, average response times were 30% longer at 27°C. For younger subjects, their RT was 33% longer at 27°C than at 21°C over the whole 60 min. For all subjects, the

Table 2. Mann-Whitney U-test of response time (mean for signals).

	21°C		27°C				
	Rank†	*N*	Rank†	*N*	M-WU	*Z*(0, 1)	2-tail *p*
Overall							
0–60 min	36·2	42	47·9	41	618·0	−2·21	<0·027
Time on task							
0–30 min	38·7	42	45·4	41	722·0	−1·27	ns
30–60 min	36·7	42	47·5	41	637·0	−2·04	<0·041
City (<60 km.h)/Higher speeds							
Speed <60 km/h	38·5	42	45·6	41	712·0	−1·36	ns
Higher speeds	38·0	42	46·1	41	694·0	−1·52	ns
Speed <60 km/h: time on task							
0–30 min	41·5	42	40·5	39	799·0	+0·19	ns
30–60 min	36·9	41	46·1	41	652·0	−1·75	ns
Higher speeds: time on task							
0–30 min	36·6	42	46·7	40	634·0	−1·91	<0·056
30–60 min	38·9	42	45·1	41	732·5	−1·17	ns
Age of driver							
Driver <40 years	19·5	25	27·4	20	162·0	−2·01	<0·044
Older drivers	18·0	17	20·7	21	153·0	−0·75	ns
Driver <40 years: time on task							
0–30 min	18·6	25	28·5	20	140·0	−2·51	<0·012
30–60 min	21·3	25	25·1	20	208·0	−0·96	ns
Older drivers: time on task							
0–30 min	21·1	17	18·2	21	152·0	+0·78	ns
30–60 min	16·1	17	22·2	21	121·0	−1·69	ns
Gender							
Male Drivers	22·5	28	30·2	23	225·0	−1·84	ns
Female drivers	14·7	14	17·9	18	101·0	−0·95	ns
Male drivers: time on task							
0–30 min	23·1	28	29·5	23	241·0	−1·53	ns
30–60 min	24·4	28	27·9	23	278·0	−0·83	ns
Female drivers: time on task							
0–30 min	16·2	14	16·7	18	122·0	−0·15	ns
30–60 min	12·9	14	19·3	18	76·0	−1·90	<0·057

$p > 0{\cdot}06$ marked 'ns'.
† Mean ranks assigned in each condition.
Negative Z indicates negative effect of heat (longer RT).
NB: Mean *ranks*, not mean values, are shown for each condition, as the calculation is based on rank-ordered data.

response time averaged over the whole 60 min was 24·02 s at 21°C and 29·28 s at 27°C, i.e. RT was 22% longer at the higher compartment temperature.

3.6. *Driver vigilance, R(360) and RT*

Table 3 shows those results of the Mann-Whitney U-test analysis of R(360) that approach significance (i.e. for which $p < 0{\cdot}10$) on a 2-tail test. The columns are set up as for tables 1 and 2. Each signal was analysed separately for the whole 60-min period, and for the two successive 30-min periods, separately for subjects aged <40 and 40+ years over the whole 60-min period, and separately for male and female subjects over

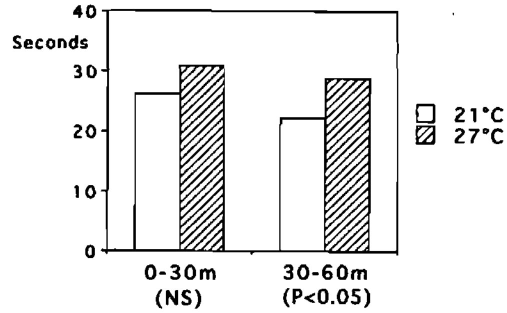

Figure 3. Mean response time (all signals) by time on task.

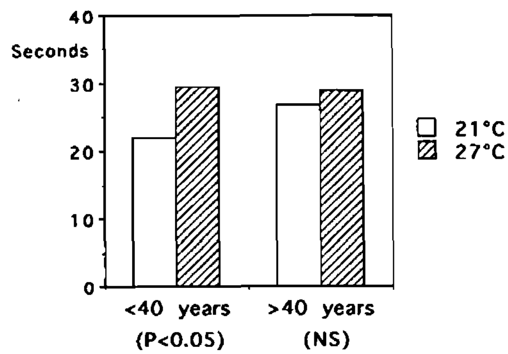

Figure 4. Mean response time by age of driver.

the whole 60-min period. The number of signals given and the mean rank are shown for each thermal condition.

Detection of the signal 'clock fast' was significantly worse at 27°C over the whole hour ($p < 0{\cdot}05$), and in the second half-hour ($p < 0{\cdot}05$). Detection of the signal 'noise rear' was significantly worse at 27°C over the whole hour ($p < 0{\cdot}005$), and in the second half-hour ($p < 0{\cdot}05$), and the thermal effect approached significance in the first half-hour ($p < 0{\cdot}063$) for this signal. Warning lights (brakes fail, parking brake or oil low) taken as one signal were detected significantly less efficiently over the whole hour ($p < 0{\cdot}02$) and in the second half-hour ($p < 0{\cdot}02$). Thermal effects on a number of other signals approached significance in the expected direction. No positive effects of heat stress on vigilance approached significance.

An analysis of RT, speed of response for correct detections, was carried out for each signal type separately, using Student's t-test on the log transform of the response time, RT. Only RT to one warning light was significantly affected by temperature ($p < 0{\cdot}05$, 2-tail) over the whole hour: RT to the 'brakes fail' signal was slower at 27°C than at 21°C. There were no significant effects in the first half-hour. In the second half-hour, men were significantly slower to respond to the 'noise rear' signal at 27°C than at 21°C ($p < 0{\cdot}05$), and women were significantly slower to respond to the 'oil low' signal at 27°C than at 21°C ($p < 0{\cdot}05$).

Table 3. Mann-Whitney U-test of response measure R(360).

	21°C		27°C				
	Rank†	N	Rank†	N	M-WU	$Z(0, 1)$	2-tail p
Overall							
RPM High	44·7	46	55·4	54	976·0	− 1·84	< 0·066
Clock fast	27·4	29	37·5	36	361·0	− 2·12	< 0·034
Oil low	37·1	47	47·4	35	617·0	− 1·93	< 0·054
Brakes fail	29·3	37	39·8	30	381·5	− 2·19	< 0·029
Noise rear	21·5	30	33·4	22	178·5	− 2·81	< 0·005
All single lights	99·4	113	120·4	105	4790·5	− 2·45	< 0·014
0–30 min							
Brakes fail	11·0	13	16·0	13	52·0	− 1·67	< 0·095
Noise rear	9·7	13	15·0	10	35·0	− 1·86	< 0·063
Police L	22·6	27	30·7	25	233·0	− 1·91	< 0·056
30–60 min							
Clock fast	9·1	9	15·2	16	37·0	− 1·98	< 0·048
Oil low	24·6	30	33·0	26	272·5	− 1·93	< 0·054
Noise rear	12·1	17	19·0	12	53·5	− 2·15	< 0·032
All single lights	59·9	69	76·5	66	1719·0	− 2·46	< 0·014

$p > 0{\cdot}10$ (2-tail) not shown.
† Mean ranks assigned in each condition.
Negative Z indicates a negative effect of heat stress on vigilance.
The tabulated results are all significant ($p < 0{\cdot}05$) for a 1-tail test of the expected negative effect of heat stress on vigilance.
NB: Mean *ranks*, not mean values, are shown for each condition, as the calculation is based on rank-ordered data.

3.7. *Detection of individual signals*

Table 4 lists those signals for which the tendency for detection to be lower at the raised compartment temperature approached significance at the ($p < 0{\cdot}06$, 1-tail) level. Only two signals were significant ($p < 0{\cdot}05$) for a 2-tail test when considered separately: RPM high and noise rear. Both were extremely difficult to detect and may be considered relatively peripheral to the main task.

3.8. *Overt lapses of attention*

Table 4 shows that a total of six female subjects were observed to make an error indicative of a lapse of attention during the third or fourth circuit: five made a wrong turning, and one failed to observe that traffic in front had stopped and narrowly avoided a collision. All six were driving in the 27°C condition, and represent 33% of the female subjects assigned to this condition. No such errors were recorded for female subjects driving in the 21°C condition. The Fisher exact probability test yields $p = 0{\cdot}020$ for a 1-tail test for the negative effect of heat stress, i.e. the effect was significant at the ($p < 0{\cdot}05$) level for a 2-tail test. Only one of the 51 male subjects made such an error. Table 4 also shows the same calculation for circuits 2–4: there was a significant negative effect of heat stress ($p < 0{\cdot}0095$) for female subjects, but not for male subjects. A lapse of attention was observed for 39% of female subjects driving at 27°C. None were observed at 21°C. One female subject made wrong turnings during circuits 3 and 4, despite having been prevented from doing so at the last minute in circuit 2. These were

Table 4. Detection of invidual signals, observed lapses of attention.

	21°C		27°C		Chi square (1 df)	1-tail p
Detection (signals)						
	Hit	*Miss*	*Hit*	*Miss*		
RPM High	14	32	4	50	8·92	$<0·01$
Generator fails	46	2	31	8	–†	$<0·05$
Noise rear	26	4	13	9	5·15	$<0·05$
Horn	40	1	20	4	–†	$<0·06$
Police L + R	85	0	57	10	–†	$<0·01$
All single lights	113	0	95	10	–†	$<0·01$
Observed lapse of attention (subjects)						
	None	*1+*	*None*	*1+*		
Males lap 3, 4	28	0	22	1	–†	ns
Females lap 3, 4	14	0	12	6	–†	$<0·02$
Male lap 2–4	27	1	21	2	–†	ns
Females lap 2–4	14	0	11	7	–†	$<0·01$

NB: In lap 2, data include when a reminder was judged to be necessary.
In laps 3–4, no reminders were given (see text).
† Expected cell frequency <5: Fisher exact calculation of p.
$p>0·06$ (1-tail) are not shown.
Effect of heat was to decrease detection of signals and increase the frequency of observed attentional lapses.

counted as only one instance in the above analysis. Only 3 of the 51 male subjects were observed to make such an error. The tendency for female subjects to provide evidence of a lapse of attention more often at 27°C than at 21°C was significant at the ($p<0·02$) level for a 2-tail test.

3.9. *Possible sources of error*

Subjects in this experiment were randomly assigned to only one of the two thermal conditions and were unaware of the purpose of the experiment. Neither condition was unusual for the time of year, and none of the subjects guessed that thermal conditions were under investigation. It is therefore unlikely that the conditions differed systematically in terms of subjects' own expectation of how their driving performance would be affected. Conditions alternated throughout each day, so external weather conditions and diurnal changes in vigilance cannot have been confounded with the effects of compartment temperature.

4. Discussion

A very moderate increase in compartment temperature, insufficient to cause observable sweating in all but a few subjects, and typically occurring in all non-airconditioned vehicles for several months during the summer, even in Sweden, has been shown to have significant negative effects on driver vigilance. These effects occurred in the first hour of driving, in spite of the fact that the subjects knew that they were taking part in an experiment, and that there was an experimenter in the back seat. The effects were not negligible: a 50% increase in the number of signals missed, and a 22% slower response time to the signals that were detected. At 60 km/h, a vehicle in which the compartment temperature was 27°C would travel 88 m further on average before the driver responded to an unexpected signal, in comparison with a vehicle in which the compartment temperature was maintained at 21°C, and the signal would remain completely undetected while the warmer vehicle traversed at least 3 km at this speed (i.e. during a period of at least 3 min) on 50% more occasions than in the cooler condition. Very few accidents occur with no forewarning at all. A vigilant driver will respond more often and more rapidly to whatever unexpected forewarning signs are available, and will more often be able to avoid critical situations altogether. Conventional vehicle safety engineering has tended to concentrate on protecting the driver once a critical situation has arisen, the driver has failed to deal with it, and this failure has led to an impact. The present results suggest that effective air conditioning may be able to substantially increase driver vigilance in warm weather, and may thereby reduce accident frequency.

The negative effects of moderate heat stress on vigilance were more marked at speeds below 60 km/h, which occurred in this experiment in city traffic rather than on the open road. They were in other words accentuated by information *overload*, rather than by information underload. Vigilance performance also decreased with time on task, but as this occurred in the first hour, it is not comparable with the effects of time on task in experiments lasting several hours, which is usually taken to decrease arousal. In the present experiment there will have been a progressive increase in the apparent complexity of the vigilance aspect of the task: subjects were initially unaware of which signals could occur, and will only gradually have realized the number of potential sources of information that they were expected to monitor. This will progressively have increased any information overload. The results are therefore compatible with the view that subjects responded to the heat stress by raising their level of arousal, instead of reducing physiological strain by lowering their level of arousal, for in this latter case information *underload* would have been expected to accentuate the behavioural effect of heat.

Raised arousal has been shown by Easterbrook (1959) to be associated with reduced cue-utilization, and Hockey (1970) demonstrated that raised arousal caused by high noise levels resulted in an alteration of the attentional field during vigilance, signals judged to be less probable being less often detected. Bursill (1958) had found that high levels of heat stress had the same effect, and in the field experiment of Mackie *et al.* (1974) cited above, peripheral signals visible only in the rear-view mirror were less often detected in an extremely hot vehicle. In the present experiment the most consistently significant effect of heat stress was on detection of the very faint and unexpected noise signal from the rear of the car and of errors introduced to the tachometer (RPM) and clock. These three signals were among the most difficult to detect and therefore, as argued by Hockey (1970), will have been perceived by the subjects to be infrequent and therefore peripheral. Although all signals were missed more often at the higher temperature, an alteration of attentional field, towards the more frequently detected signals, appears to have taken place at 27°C. This bias is similar to the reported effects of raised arousal.

No physiological measures were taken in the present experiment, and an increase in arousal in response to moderate heat stress while driving can only be inferred. However, if this is the correct interpretation of the observed results, the direction of the effect is the opposite of that found in stationary experimental settings. This may be because it is possible to relax in a stationary workplace, in order to reduce muscle tension and metabolic rate, while the driver of a moving vehicle should be aware that any tendency to relax concentration is potentially dangerous. Even quite moderate levels of heat stress may therefore have an initial arousing effect if a driver over-reacts, exerting too much effort to maintain arousal. This may be followed by increasingly frequent but brief episodes of involuntary relaxation (lapses of attention) when it becomes impossible to continue to counteract the relaxing effect of the heat. Future research should be aimed at confirming the direction of the effects of moderate heat on the arousal level of the drivers of moving vehicles, and the nature of any decrement with time on task over periods of several hours. It is worth noting that this work cannot usefully be carried out in stationary simulators.

There is very little evidence for gender difference in the vigilance data: male drivers missed significantly more signals in the second half-hour, while female drivers did not, but there was an almost significant tendency ($p < 0{\cdot}06$) for female drivers to respond more slowly in the second half-hour, while male drivers did not. The gender difference was more marked in the record of actual driving errors: almost 40% of the female subjects who drove at 27°C made a wrong turning or similar error indicative of a temporary lapse of attention, while no female subject who drove at 21°C did so, a difference that is significant at the ($p < 0{\cdot}01$) level. No such effect of heat stress was observed for male subjects.

There is also little evidence for age differences in response to heat, for while it is true that all of the significant effects reported were for younger drivers, the effect of heat on detection of signals over the whole hour by older subjects was very close to formal significance ($p < 0{\cdot}052$), and in the same direction, i.e. heat stress decreased the vigilance of both age groups.

The technique of measuring vigilance by introducing unexpected signals of a kind to which drivers must always be alert into the task of driving a moving vehicle on a public road has been shown to be sensitive to moderate heat. As the dependent measure is part of the actual task of driving it could equally well be used to examine the effects of opening a window to avoid heat stress, and therefore accepting raised levels of draught and low-frequency noise instead. It would also be an appropriate way of quantifying performance decrement over longer periods than one hour in a hot vehicle, and of various others ways of improving vigilance performance under hot conditions, such as air-conditioning, better distribution of cooling power over the body surface of the driver, lower noise levels, filtering of supply air, ventilated seats and an improved work, rest and sleep schedule.

5. Conclusions

Driver vigilance was significantly lower when compartment temperature was maintained at 27°C, in comparison with 21°C, when subjects who were randomly assigned to these two conditions drove on the public road for 60 min. The negative effects of raised compartment temperature on vigilance were more marked in the second half-hour and at speeds below 60 km/h, i.e. in city traffic, in comparison with driving on the open road.

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