

INITIAL THERMAL SENSATION RESPONSES TO SIMULATED SOLAR RADIATION

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INTRODUCTION

Solar radiation can have a powerful influence on human thermal sensation, particularly in vehicles and buildings. Thermal comfort studies traditionally have focussed on the steady state response after prolonged exposure to an environment (30 to 120 minutes). Solar radiation can expose people to large short duration increases in radiant temperature. The responses of people exposed to a sudden change in radiant temperature on thermal sensation is not clear. These responses are of particular value to researchers who are interesting in transient environmental conditions and their effects on people within them.

This paper examines the initial responses, physiological and subjective, of participants exposed to a range of simulated solar radiation intensities on thermal sensation and comfort over a short period of time, 5 minutes.

METHODS

The data presented here comes from a series of studies which all used an identical experimental protocol.

A purpose built insulated and air conditioned environment was constructed which would provide a thermally neutral environment, $PMV = 0 \pm 0.5$, (ISO 7730: 1994). One end wall had a 45° angled frame, which had, 1m x 1m panels into which glazing panels could be fitted, Figure 1. The test chamber was divided into two separated test cells, each with a car seat which was fitted to a moveable base platform,. This base was fitted with tracking that allowed the seat to be withdrawn from the direct radiation. Fans blew air rapidly across the outside of the windows to prevent temperature build-up and hence reduce any effects of re-radiation from the window to the subject.

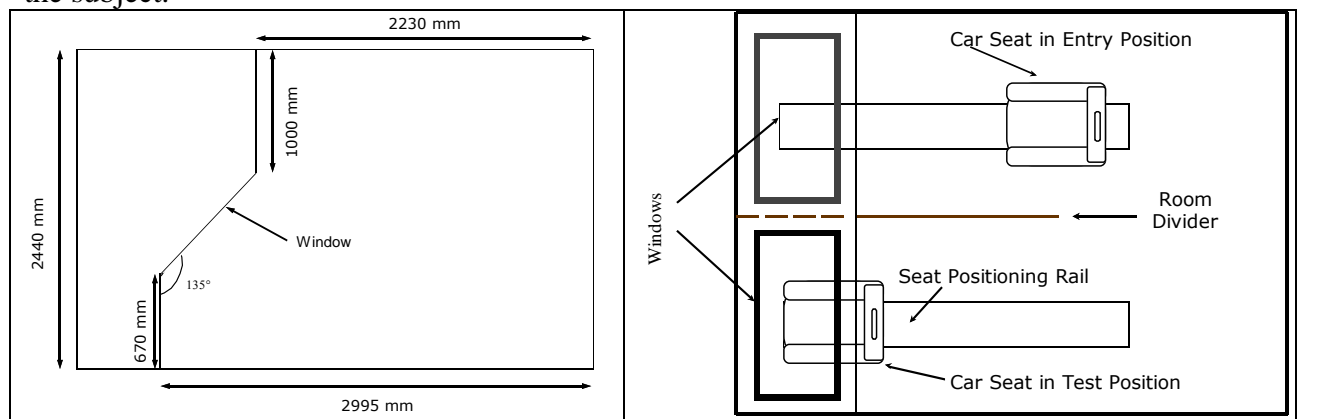


Figure 1 – Side and plan elevations of the simulated solar radiation chamber

The bank of Solar Simulation lamps (1000 Watt metal halide, CSI lamps, GE Lighting) which produce light with a spectrum similar to that of sunlight, Beeson (1978), were used as a radiation source. The intensity of the radiation falling on the subject was controlled by the distance of the lamps from the subject. This preserved the spectral content of the energy from the lamps. Participants were exposed to a range of simulated solar radiation intensities from 200 to 625 Wm^{-2} .

Mean skin temperature, Ramanathan (1964), and two local skin temperatures, forehead and forearm, were recorded.

A modified ISO 7 point thermal sensation scale was used to provide a more sensitive scale to measure the effects of the solar radiation. The thermal sensation scale was extended a further 2 points, (4 – very hot and 5 – extremely hot), based upon the principles of ISO 10551 (1995) and a wider scale of thermal sensation described by Givoni (1976).

The scale used a continuous Likert rating, rather than discrete points. This allowed the subject to mark the vertical line precisely at the point which represents their thermal sensation, (e.g. +1.5, indicates a sensation between slightly warm and warm). Participants gave ratings of thermal sensation, comfort, stickiness and preference in terms of both overall feeling and over local areas of the body.

In total, twenty five, healthy, male volunteers (Age 26.5 ± 4.1) were recruited. All subjects were exposed to at least 3 of the conditions. The participants were paid upon completion of all conditions.

Participants wore a specified clothing ensemble of white cotton/polyester (65/35%) long sleeve shirt, (sleeves rolled up above elbow), beige cotton/polyester (65/35%) trousers, and the participants wore their own under garments and shoes giving an estimated clo value of 0.7 (including seat), (ISO 7730). The seats used were of the type fitted to the 'Fiat Punto' (circa 1998).

The subject's head was shielded. This meant that no direct radiation was exposed to their face/eyes and that the area of the body irradiated was the torso (from the neck down), arms and thighs of the subject.

For all studies the environmental chamber was controlled in order to maintain a constant 'neutral' environment condition, $\text{PMV} = 0 \pm 0.5$ (ISO 7730) when the effect of the direct radiation was not considered. The air temperature, (t_a), mean radiant temperature (t_r) = t_a , relative humidity (rh%) and air velocity (ms^{-1}), participants' clothing and their metabolic rate, remained 'constant' at levels that provided a neutral environment.

Environmental conditions were monitored and measured throughout the experimental chamber; t_a in a number of positions with thermistors, at the subject's knees, head height, and shaded from direct radiation, t_r using a 150 mm diameter black globe next to the subject, and one behind the subject, (shaded), air velocity with a hot wire anemometer next to the subject and rh(%), behind

the subject with a Vassala chip meter. Direct radiation was measured with a Kipp and Zonen CM11 Pyronometer.

The participants had a series of six skin thermistors fitted to various body parts and then got dressed in the standard clothing provided. The thermistors were fitted into Eltek / Grant squirrel data loggers and recordings were taken every ten seconds. Participants only undertook the experiments when it had been determined via the questionnaire that they were in a thermal neutral state.

The participants were taken into the neutral environmental test chamber. They were seated in the car seat, (out of the direct simulated solar radiation), and they completed a questionnaire to ensure that they were still feeling neutral. When both participant and experimenter were satisfied the experiment commenced and the subject's seat was pushed into the forward position into the direct solar radiation and they were handed the first experimental questionnaire to complete. This was time mark 'zero', the subject then completed a questionnaire after five minutes from this time. Participants were asked to keep their left arm still during the experiment using the right to complete the questionnaires, which were handed to them by the experimenter.

RESULTS

For analysis purposes results were grouped by radiation intensity to which the participants were exposed. Statistical analysis of the changes between the responses at zero and 5 minutes were evaluated with a Wilcoxon sign test.

Environmental conditions

Table 1 presents a summary of the environmental data for the various conditions.

Table 1 – Summary of experimental environmental conditions

	625 Wm ⁻² (n=9)	600 Wm ⁻² (n=26)	400 Wm ⁻² (n=40)	300 Wm ⁻² (n=18)	200 Wm ⁻² (n=8)	0 W m ⁻² (n=*)
t _a shielded (°C)	24.30	24.07	22.78	22.45	23.40	22.80
t _r (°C) derived from t _g	37.50	42.75	37.06	34.50	37.70	24.20
Air Velocity (m/s)	0.10	0.09	0.10	0.10	0.10	0.10
Relative Humidity (%)	31.60	42.65	49.98	50.10	51.40	48.30
PMV*	0.20	0.13	0.18	0.20	0.10	0.10
PMV ⁺	2.7	2.7	1.78	1.3	1.1	0.2

PMV* calculated with t_r = t_a

PMV⁺ calculated with t_r = measured t_r

It can be seen from Table 1 that for all experimental conditions the predicted level of thermal comfort as calculated from ISO 7730 remained within the 0 ± 0.5 PMV tolerance, when t_r = t_a, as set a priori. Whilst, it can be seen that when the actual t_r is placed into the thermal comfort equation, the simulated solar radiation loads change the environments from approximately neutral (PMV = 0) to warm (PMV = 2) to hot (PMV = 3). The introduction of a directional source of radiation, had a significant effect on the mean radiant temperature as derived from globe temperature t_g.

Mean skin temperature

Figure 2 represents the mean of mean skin temperature responses of the participants during the initial exposure to the various levels of simulated solar radiation.

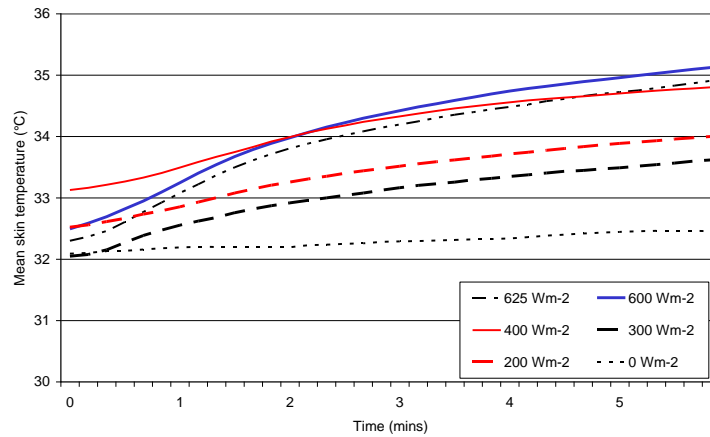


Figure 2 – Mean of mean skin temperatures for all radiation conditions.

It can be seen that mean skin temperature increases rapidly upon exposure to direct simulated solar radiation. The higher intensities showed the largest increases, (approximately 2°C), during the 5 minute exposure. This is driven in part by changes in chest and upper arm local skin temperatures. There were significant increases ($p < 0.01$) between 0 and 5 minutes for the 300, 400, 600 and 625 Wm⁻² radiation groups. There were no significant increases for the lower intensities, (200 Wm⁻² and less).

Thermal sensation

Subjects recorded their thermal sensation at zero minutes (as soon as they were exposed) and at five minutes. Figure 3a presents the mean thermal sensation data and standard deviations. There were significant increases ($p < 0.01$) between 0 and 5 minutes for the 300, 400, 600 and 625 Wm⁻² radiation groups. There were no significant increases for the lower intensities, (200 Wm⁻² and less).

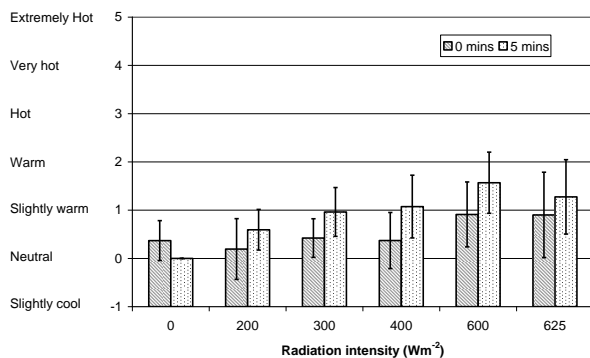


Figure 3a – mean thermal sensation votes

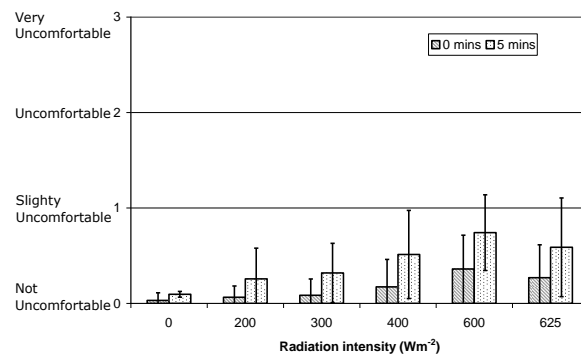


Figure 3b – Mean thermal comfort votes

When the thermal sensation results are compared with the thermal comfort responses it can be seen that for radiation levels up to 400 Wm⁻² there is very little discomfort reported, Figure 3b.

This is possibly because the participants actually liked the addition of the radiation at this point, this was supported by anecdotal evidence from the participant post experiment.

CONCLUSIONS

1. Exposure to direct simulated solar radiation results in immediate increases in exposed skin temperature.
2. Exposure to direct simulated solar radiation elicits an instantaneous thermal sensation response, even at relatively low intensities.
3. Significant changes in thermal sensation occur within 5 minutes for radiation intensities of 300 Wm^{-2} or more.
4. Increases in thermal comfort ratings lag behind those seen in thermal sensation, with lower intensities being perceived as pleasant.

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