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THE EFFECTS OF INFRARED-REFLECTIVE TREATMENT ON THERMAL COMFORT DURING TRANSIENT CONDITIONS

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16. Abstract

Four otherwise identical sedans had an infrared-reflective (IRR) film applied to differing sections of the vehicles' glazing. An experiment was performed using two independent variables: air conditioning output (two different settings) and IRR film placement (windshield and front side windows, windshield only, front side windows only, and no IRR film applied). Dependent variables included subjective assessments of thermal comfort as well as objective measures of skin temperature and cabin air temperature.

Presence of the film significantly decreased skin temperature and cabin air temperature. Not surprisingly, the magnitude of this effect was larger in those conditions where larger surface areas of film were applied. Presence of the film was also associated with a significant increase in subjective assessments of thermal comfort, an increase that appeared to be at least partly independent of the air temperature inside the vehicle. That is, for any given air temperature subjective ratings of thermal comfort were better in those conditions in which the IRR film was applied.

The data from this study support the conclusion that IRR treatment can reduce the time required to reach comfort during vehicle cool-down. Further research should examine the relationship between subjective ratings of thermal comfort and the reduction in radiant heat that is associated with IRR treatment.

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CONTENTS

INTRODUCTION

A literature review was recently completed on the effects of infrared-reflective (IRR) glazing on thermal comfort (Devonshire & Sayer, 2002). In the review, the results of eight experimental studies of IRR glazing were presented along with a general overview of thermal comfort in automotive environments. The major findings from this review are outlined below.

Adding IRR treatment to a vehicle's glazing has been shown to reduce cabin air temperature and surface temperatures of the dashboard and instrument panel under conditions of high solar load. Further, evidence suggests that IRR treatment is more effective at maintaining cabin air temperatures than infrared-absorbing treatment. This is due to the lack of "re-radiation" of heat into the vehicle's cabin that is commonly observed with infrared-absorbing treatment.

Though past research is limited by a lack of statistical analyses, the lower temperatures associated with IRR glazing treatment are fairly consistent findings; all eight of the reviewed studies found either lower peak soak temperatures or reduced cool-down times when an IRR treatment was applied to the glazing. Not surprisingly, the reductions in temperature were correlated with the amount of treatment used and the percentage of infrared radiation rejected by the treatment.

Attention has been given to two possible applications of these findings. First, lower temperatures inside the vehicle cabin may increase fuel economy because the air conditioning (A/C) system would not have to work as hard at maintaining a comfortable climate. This, in turn, could lead to smaller engine and/or A/C compressor sizes. The second application involves the comfort of vehicle occupants. Lower soak temperatures and cool-down times may translate into increased thermal comfort when occupants enter their car, particularly after the car has been sitting in the sun for prolonged periods.

Although past research has examined the potential of IRR glazing treatment to positively affect thermal comfort, experimental studies have only used objective measures of vehicle climate (such as air temperature) in their designs. None of the eight research articles reviewed by Devonshire and Sayer measured subjective assessments of comfort. In addition, only three of the studies used "thermal comfort meters" (instruments designed to measure all of the environmental parameters associated with thermal comfort). Because thermal comfort has been linked to the combined effect of air temperature, air velocity, humidity, mean radiant temperature, clothing level, and activity level, studies that measure only IRR glazing treatment's affect on air temperature may be missing important elements related to occupant thermal comfort.

Moreover, the absence of subjective assessments of comfort means that researchers have to rely on models of thermal comfort to predict how people might respond when an IRR treatment is used. Because existing models of thermal comfort were not developed for automotive applications, these models may give an inaccurate sense of how people would actually respond.

The present study investigated measures of climate and thermal comfort during a stationary vehicle cool-down with an IRR film applied to the vehicle's glazing. The study was designed to answer the following questions:

(1) Is there a statistically reliable reduction in cabin air temperature due to IRR treatment of the vehicle's glazing?

(2) Does adding an IRR treatment to a vehicle's glazing affect subjective ratings of comfort?

(3) In what way do objective measures of climate relate to subjective ratings of comfort in a vehicle cabin? Does air temperature alone predict how subjects rate their comfort, or might other factors such as radiant heat play an important role?

METHOD

Independent variables

The study employed a 2 x 4 repeated measures design (each subject experienced all levels of the two independent variables, resulting in eight experimental conditions per subject). The presentation order of the stimuli was counterbalanced according to a modified Latin square design. Independent variables included air conditioning level and IRR film placement.

Air conditioning level

Two different settings were used for the air conditioning level: maximum fan speed with air recirculation, and high fan speed without air recirculation. The high fan speed was one level below the maximum setting (the vehicles had four possible fan speed settings, and a separate control was adjusted to manipulate the air recirculation mode).

IRR film placement

An aftermarket IRR film was applied to specific parts of the vehicles' glazing. Four vehicles were used for the experiment, and each had a different configuration of IRR film placement (naming conventions are indicated in parentheses and will be used throughout the remainder of the report):

Car 1 ("fully treated"): Film was applied to the windshield and the two front side windows.
Car 2 ("windshield"): Film was applied to the windshield only.
Car 3 ("side windows"): Film was applied to the front side windows only.
Car 4 ("untreated"): No IRR film was applied (control).

Dependent variables

Subjective measures

Subjects were asked to give periodic ratings of both thermal sensation and thermal comfort. Thermal sensation and thermal comfort were measured with two numerical rating scales suggested by *ISO 10551: Ergonomics of the thermal environment—assessment of the influence of the thermal environment using subjective judgment scales* (1993). These scales are commonly used by the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), and are based primarily on the experimental work of Fanger (1970).

Thermal sensation was measured by the following numerical scale:

Very hot	+4
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3
Very cold	-4

Subjects used this thermal sensation scale to give three different ratings: overall (whole body) thermal sensation, left forearm thermal sensation, and right forearm thermal sensation.

Thermal comfort was measured by the following numerical rating scale:

Comfortable	0
Slightly uncomfortable	1
Uncomfortable	2
Very uncomfortable	3
Extremely uncomfortable	4

Subjects used the thermal comfort scale to give one rating, an overall (whole body) comfort rating. The two separate rating scales were used to examine the relationship between how hot or cold the subjects felt and how comfortable they were with those sensations. For example, one person may rate a sensation as slightly warm and comfortable, while another person may find the same sensation uncomfortable.

ISO 10551 suggests that the central tendency of subjects' perceptual judgments (obtained by using either one of these scales) yields a measure that can be compared to standardized thermal comfort indices. These indices are known as the *Predicted Mean Vote* (PMV) and *Predicted Percentage Dissatisfied* (PPD) (Fanger, 1970). The indexes were designed to determine how a given combination of environmental parameters would affect subjective assessments of thermal comfort.

Objective measures

Objective measures included mean skin temperature (an average, weighted according to relative surface area of skin, of four different locations on the body: neck, right scapula, left hand, and right shin) and mean air temperature (an average of two sites within the vehicle cabin).

Materials

Vehicles

Four late-model, four-door sedans were used. They were identical in make, model, year, exterior color, and interior trim (gray cloth upholstery and dark gray dashboard). The total surface area of the glazing on each vehicle was approximately 2.3 m^2. Each vehicle was equipped with the original factory-installed glazing.

IRR film

An aftermarket IRR film was used for the experiment. Table 1 lists the specifications of the film, as provided by the manufacturer. Notice that the film had a visible light transmittance of about 77.0% and rejected 77.0% of IR radiation.

Table 1
IRR film specifications.

Visible light transmittance:	77.0%
IR rejection:	77.1%
UV rejection:	99.0%
Shading coefficient:	0.6
Emissivity:	0.6
U-Value:	1.0

The film included its own adhesive backing, and a water/glycerin combination was used to apply the film to the exterior of the glazing.

Instruments

Insulated type-T thermocouples were used to measure skin and air temperatures. Additionally, a small weather station was used to take measurements of ambient (outdoor) air temperature, wind speed, and wind direction (one measurement was taken at the beginning of each trial). Campbell Scientific® data loggers were used to collect air and skin temperature measurements, while ambient weather data were recorded by hand.

Experimental setup

The experiment was performed outdoors at UMTRI. The four cars remained stationary throughout the experiment, and they were placed approximately 10 feet apart from one another along one horizontal row (facing due west). Figure 1 shows how the cars were positioned.

Figure 1. Positions of the four vehicles.

Each car had matte black aluminum foil taped onto the roof to maximize solar absorption. Two thermocouples were placed in the same locations in each of the four cars: on the ceiling (about two inches behind the overhead dome light) and on the front-center instrument console. The measurement of air temperature inside the cabin was the average of the two thermocouple readings. Both of these thermocouples were positioned so that direct sunlight could not affect the readings.

Figure 2 shows some of the instrumentation as installed. All of the sensors were located in the front of the vehicle cabin, and data loggers were positioned on the back seat.

Figure 2. Interior of one vehicle (all four were the same).

Subjects

There were 12 paid subjects, recruited from a list of potential volunteers that is maintained by UMTRI. Six were in a younger age group (between 18 and 30 years old with a mean age of 23.0 years) and six were in an older age group (between 45 and 60 years old with a mean age of 49.7 years). The subjects were balanced for gender, and all subjects were licensed drivers. Each subject was given a standard set of clothes to wear that included a white T-shirt, navy blue shorts, and white cotton socks. The subjects were allowed to wear their own undergarments and shoes (if the shoes were not open-toed or sandals). During the experiment, subjects had thermocouples taped to their skin, with connectors attached to their clothes via safety pins.

Procedure

All experimental sessions were performed between July 25 and August 7, 2002. Subjects were assigned to either a morning session that began at 11:00 a.m., or an afternoon session that began at 2:00 p.m. There were six morning and six afternoon sessions.

At the beginning of each trial, the subject was led from the UMTRI building (a controlled climate) to one of the four cars. The subject was instructed to approach the driver's side door, but to wait until the experimenter signaled before entering the car. When the experimenter signaled, both the subject and the experimenter entered the car simultaneously (the experimenter entered through the rear passenger side door) and closed the doors as quickly as possible.

Once inside the vehicle, the subject placed his/her hands at predefined locations on the steering wheel and waited for the experimenter to plug in the skin temperature thermocouple connectors (approximately 10-15 seconds). When this was completed, the subject was asked to give initial ratings of thermal sensation and comfort (copies of the rating scales were posted on the front center panel in the vehicle cabin). After the initial ratings, the subject was asked to start the car and wait until he/she was prompted for ratings. Ratings were given every 30 seconds for a total of five minutes, at which point the experimenter asked the subject to turn off the engine. When the engine had been turned off, the trial was complete and the subject was disconnected from the thermocouples and led back inside the UMTRI building for 10 minutes of temperature adaptation before the next trial began.

The exact wording of the instructions (read to the subjects inside the UMTRI building before the first trial began) was as follows:

> Today's procedure will work in the following way: At the beginning of each trial, the experimenter will lead you outside to one of the cars in the parking lot. Only when the experimenter prompts you to enter the car (not before), please open the driver's side door and enter the car **as quickly as possible**. You do not need to worry about putting on your seatbelt or making any adjustments to the seat or other controls. Just open the door, get into the driver's seat, and close the door as soon as you can. Again, you should not make any adjustments to the car's interior….
>
> Once the car is started, you will be asked to give thermal comfort ratings every 30 seconds until a period of five minutes has elapsed. Do not worry about keeping track of time – the experimenter will prompt you for ratings every 30 seconds and will let you know when the five minutes are over. After five minutes, the experimenter will ask you to turn the car off. Again, all you need to do is turn the ignition to the "off" position.

> Once the car has been turned off, the experimenter will disconnect the attachments to your clothes and you will be led back into the cafeteria-area for 10 minutes before the next trial begins. There will be a total of eight trials today….
>
> To give a rating, simply call out the number that corresponds to how you feel at that moment. The experimenter will record your responses. While you are giving your ratings, please feel free to refer to the copies of the scales you will be using. They will be mounted on the dashboard for your convenience. Also, when giving your ratings, please try not to base them on past ratings. In other words, do not try to remember what kinds of ratings you gave in previous trials. During each individual trial, give ratings that correspond to *how you feel at the present moment*.
>
> Again, the cycle of four thermal comfort ratings (three hot/cold ratings and one comfort rating) will be repeated every thirty seconds after you have started the car until a period of five minutes has elapsed, at which point the experimenter will ask you to turn the car off.
>
> We urge you again to notify the experimenter immediately if at any time you feel dizzy, light-headed, or otherwise too uncomfortable to continue. Remember that water will be available to you whenever you are not in one of the cars.
>
> Before we get started, do you have any questions?

Two complete sets of equipment were used with the four cars. Between trials, the set of measuring equipment (data loggers, transducers, etc.) that had just been used was moved to another car. If the first four trials, for example, were in cars 1, 2, 3, and 4, respectively, the experimental equipment would initially be located in cars 1 and 2. When the first trial was completed, the equipment from car 1 would be moved to car 3. When the second trial was completed, the equipment from car 2 would be moved to car 4, and so on until the end of the experimental session. In this way, each car was given an opportunity to resoak in the sun before being tested again in a new trial.

RESULTS

Ambient weather

Ambient (outdoor) air temperature and wind speed/direction were recorded once per trial (eight measurements per subject). Figure 4 shows the average ambient air temperature (over the eight trials) for each subject. The average temperature ranged from 70.1° F (21.2° C) to 94.1° F (34.5° C), with an overall mean temperature (across all trials and subjects) of 84.0° F (28.9° C). The standard deviation of ambient temperature between subjects was 8.0° F. The standard deviation within subjects (between trials) was 1.3° F. In other words, though different subjects experienced different ambient air temperatures, the temperature changed only slightly throughout each experimental session.

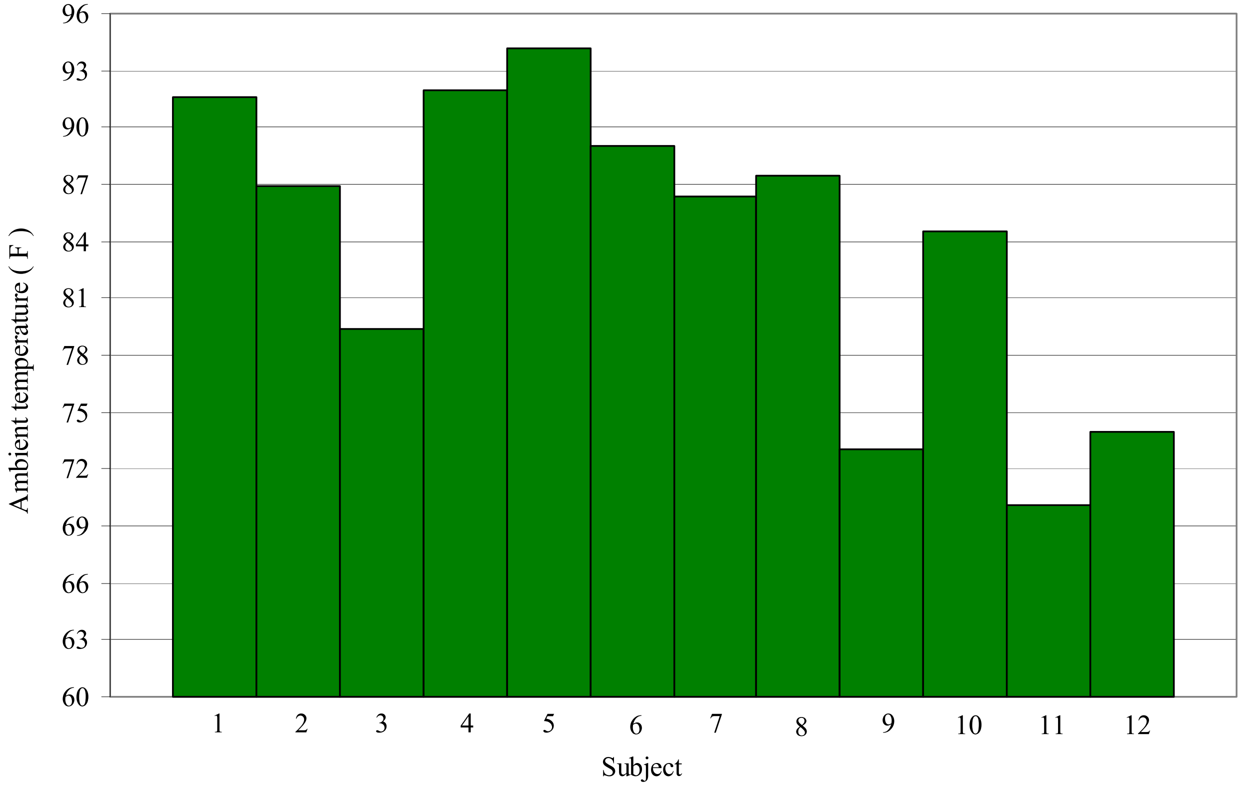

Figure 4. Average ambient air temperature (° F) over the experimental session for each subject.

As mentioned previously, there were six morning sessions and six afternoon sessions. The average ambient air temperature for the morning sessions (lasting approximately from 11:00 a.m. to 2:00 p.m.) was 81.3° F (27.4° C). The average ambient air temperature for the afternoon sessions (lasting approximately from 2:00 p.m. to 5:00 p.m.) was 86.8° F (30.4° C). Thus, the afternoon sessions, on average, were 5.5° F warmer than the morning sessions.

The average wind speed across all trials and subjects was 2.8 mi/h (4.6 km/h). The wind direction was most often north or northeast.

Although tests were not run during active precipitation, not every experimental session was free from cloud cover. Table 2 presents information from Ann Arbor municipal airport (retrieved from http://www.wunderground.com) for each experimental testing day (blank cells indicate that no tests were run). The table gives a general sense of cloud cover throughout the course of each experimental session. Note that three days of experimental testing were characterized by mostly or partly cloudy conditions (four subjects were run during these days).

Table 2
Cloud-cover during experimental sessions.

Day	Time						
	11:00a.m.	12:00p.m.	1:00p.m.	2:00p.m.	3:00p.m.	4:00p.m.	5:00p.m.
July 25	Clear	Clear	Partly Cloudy	Clear			
July 31	Clear	Partly Cloudy	Clear	Clear	Clear	Clear	Clear
August 1				Clear	Clear	Clear	Clear
August 2	Clear	Clear	Clear	Clear	Clear	Clear	Clear
August 3	Partly Cloudy	Clear	Partly Cloudy	Clear	Clear	Clear	Clear
August 5	Overcast	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy			
August 6	Partly Cloudy	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy	Partly Cloudy	Scattered Clouds	Partly Cloudy
August 7	Scattered Clouds	Mostly Cloudy	Mostly Cloudy	Mostly Cloudy			

Objective measures

For all objective measures, data from only 10 subjects are reported because of incomplete data for two subjects. An alpha level of .05 was used for all statistical tests.

Skin temperature

Tables 3 and 4 list the mean skin temperature across 10 subjects for each level of the two independent variables. The values in Table 3 are collapsed over A/C condition, and the values in Table 4 are collapsed over IRR film placement condition (this is true of all similar tables that follow in this report).

Table 3
Skin temperature by IRR film placement.

IRR film placement	Mean skin temperature
Fully treated	93.3° F (34.1° C)
Windshield	93.4° F (34.1° C)
Side windows	93.6° F (34.2° C)
Untreated	94.6° F (34.8° C)

Table 4
Skin temperature by A/C level.

A/C level	Mean skin temperature
Maximum	93.2° F (34.0° C)
High	94.3° F (34.6° C)

A repeated measures analysis of variance was performed that included two within-subjects variables (IRR film placement and A/C level) and two between-subjects variables (age and gender). The effect of IRR film placement was statistically significant, $F(3, 18) = 14.1$, $p < .01$. Although skin temperatures resembled what one would expect for the different A/C levels (i.e., the maximum A/C setting was associated with a lower mean skin temperature), the difference between A/C settings was not statistically significant. The effects of age and gender were also not significant.

Figure 5 shows mean skin temperature over the course of the five-minute trial averaged across 10 subjects. The measurements in Figure 5 began 15 seconds before the air conditioner was turned on in the vehicles, and measurements were made at five-second intervals. Note that the mean skin temperatures still rose for a brief period after the air conditioner was turned on.

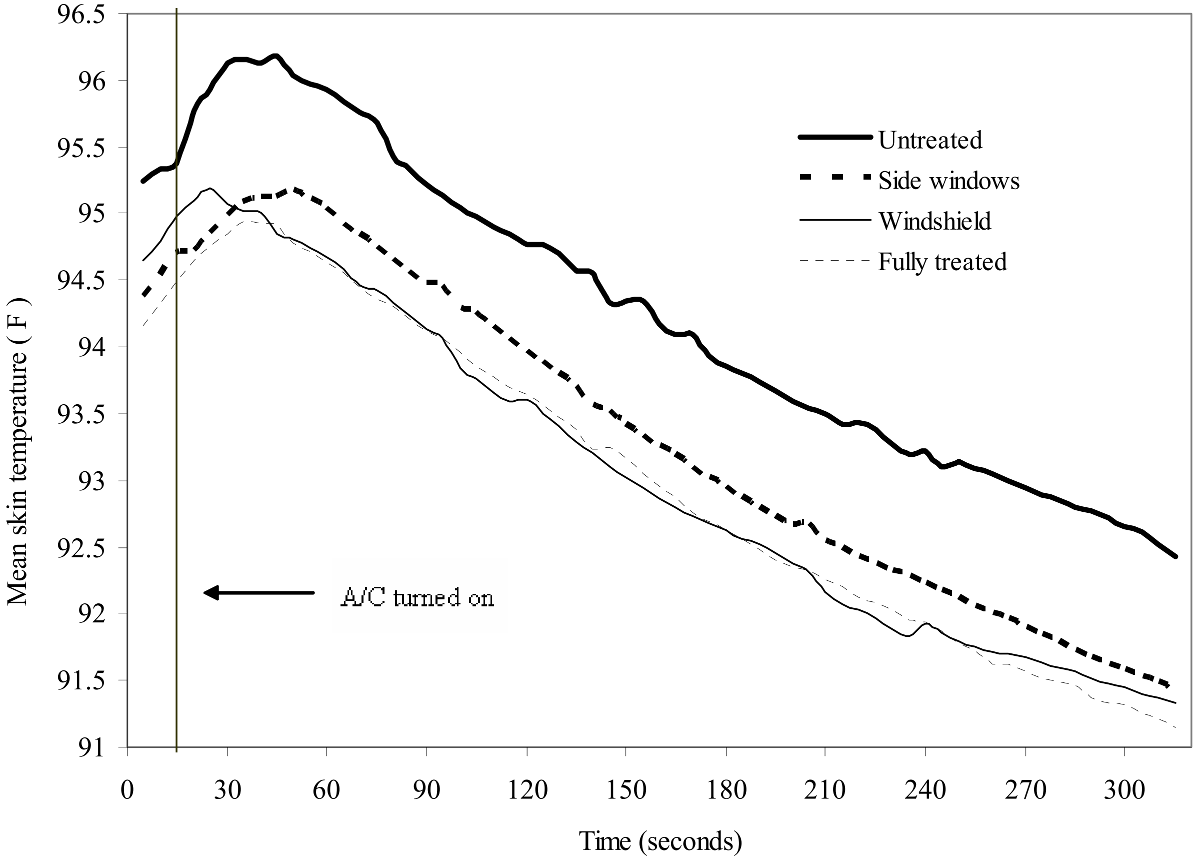

Figure 5. Mean skin temperature as a function of time.

Air temperature

Tables 5 and 6 list the mean air temperature across 10 subjects for each level of the two independent variables.

Table 5
Air temperature by IRR film placement.

IRR film placement	Mean air temperature
Fully treated	100.9° F (38.3° C)
Windshield	96.6° F (35.9° C)
Side windows	98.7° F (37.1° C)
Untreated	99.5° F (37.5° C)

Table 6
Air temperature by A/C level.

A/C level	Mean air temperature
Maximum	96.4° F (35.8° C)
High	101.4° F (38.6° C)

Another repeated measures analysis of variance was performed on air temperature that included two within-subjects variables (IRR film placement and A/C level) and two between-subjects variables (age and gender). Again, the effect of IRR treatment was statistically significant, F(3, 18) = 5.2, $p < .01$. The marginal means (Table 5) indicate that the difference among the windshield, side windows, and untreated conditions resembled the observed measures of skin temperature (the untreated condition had the highest air temperature of those three conditions). However, the mean air temperature in the fully treated car was higher than all other conditions. Pairwise comparison tests indicated that the difference between the windshield and untreated conditions was statistically significant, and the difference between the side windows and untreated condition was marginally nonsignificant ($p = .06$). The difference between the fully treated and windshield condition was also significant, but in the opposite direction of what one might anticipate.

The effect of A/C level was significant, F(1, 6) = 7.1, $p < .05$. As expected, the marginal means (Table 6) indicate that the mean air temperature was lower in the maximum A/C condition. Finally, the effects of age and gender were not significant.

Figure 6 shows mean air temperature over the course of the five-minute trial (averaged across 10 subjects). As with mean skin temperature, mean air temperature measurements were taken at five-second intervals, and the data points in Figure 6 begin 15 seconds before the air conditioner was turned on.

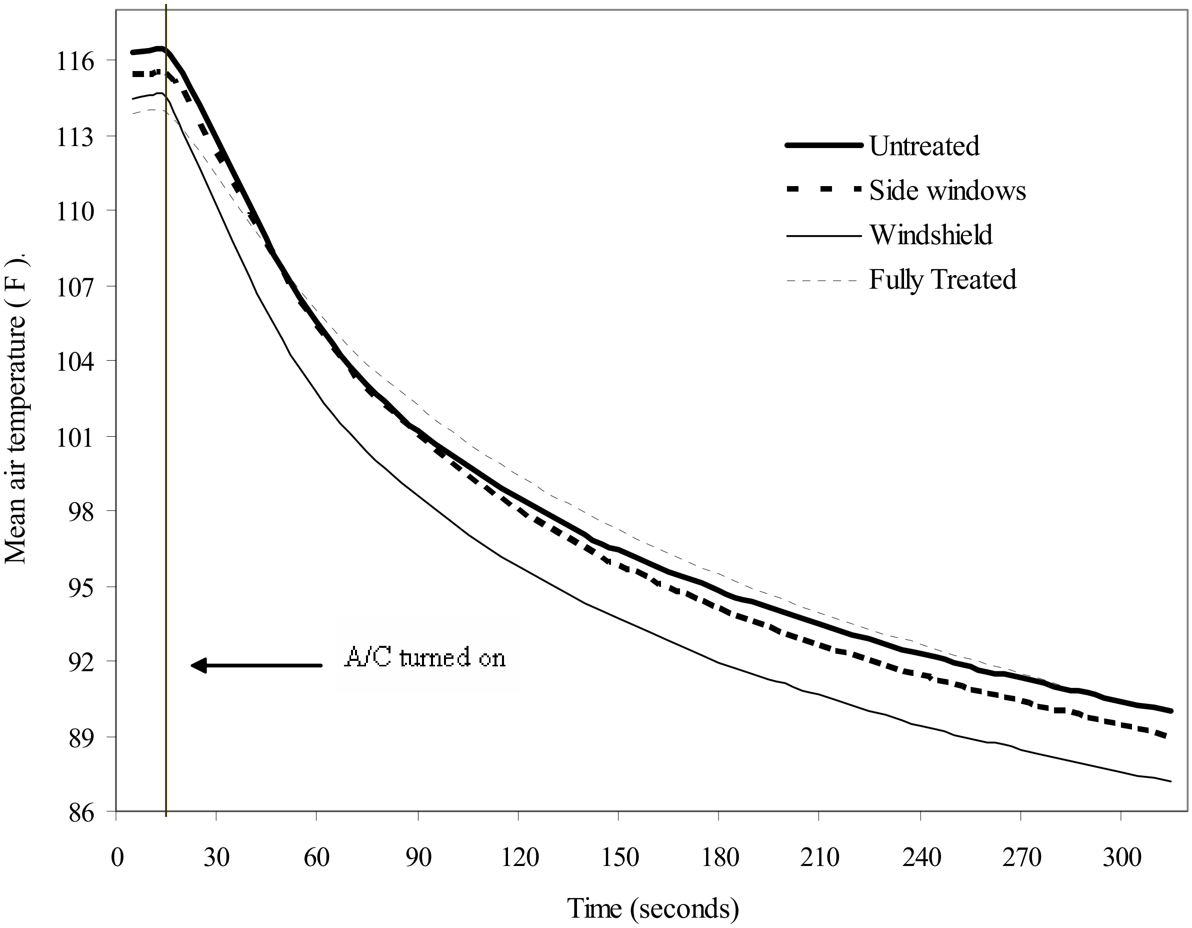

Figure 6. Mean air temperature as a function of time.

Notice in Figure 6 that the ordering of the mean air temperatures in the vehicles was different between the beginning and end of the five-minute trial. That is, the fully treated car was several degrees cooler than the untreated car at the beginning of the trial, but the fully treated car did not cool down as rapidly. The side windows and windshield conditions, however, followed a consistent pattern, both lower in mean air temperature than the untreated condition at all points.

The initial air temperature differences among conditions (the first three data points of each line in Figure 6) were not statistically significant, although the directions of those differences were consistent with what might be expected (e.g., the initial air temperature for the untreated condition was, on average, 2.5° F higher than the initial temperature in the fully treated condition).

Subjective measures

Analyses for subjective measures include data from all 12 subjects. Whole-body thermal sensation is examined, followed by whole-body thermal comfort. Finally, analyses of thermal sensation for both forearms are presented.

Thermal sensation

Tables 7 and 8 list the mean whole-body thermal sensation (hot/cold) rating across all subjects for each level of the two independent variables.

Table 7
Hot/cold rating by IRR film placement
(-4 = very cold; 0 = neutral; +4 = very hot).

IRR film placement	Hot/cold rating
Fully treated	0.90
Windshield	1.02
Side windows	1.25
Untreated	1.36

Table 8
Hot/cold rating by A/C level
(-4 = very cold; 0 = neutral; +4 = very hot).

A/C level	Hot/cold rating
Maximum	0.91
High	1.36

A repeated measures analysis of variance was performed on thermal sensation ratings that included two within-subjects variables (IRR film placement and A/C level) and two between-subjects variables (age and gender). The effect of IRR film placement was significant, F(3, 24) = 3.8, $p < .05$. The marginal means (Table 7) followed a pattern very similar to skin and air temperatures; recall that a rating of zero indicates neutral (or the absence of) thermal sensation, and that higher numbers indicate hotter sensation.

The effect of A/C level was marginally nonsignificant ($p = .06$), but the direction of the effect was as one might expect, with ratings tending to be lower (cooler) for the maximum A/C condition.

Finally, there was a significant effect of gender on thermal sensation ratings, F(1, 8) = 21.9, $p < .01$. The average sensation rating for males was 0.12, compared to a rating of 2.15 for females. That is, females on average reported hotter thermal sensation than males. There was no effect of age.

Figure 7 shows mean thermal sensation ratings over the five-minute trial. Ratings were taken at 30-second intervals, and were lowest in the fully treated condition at all points.

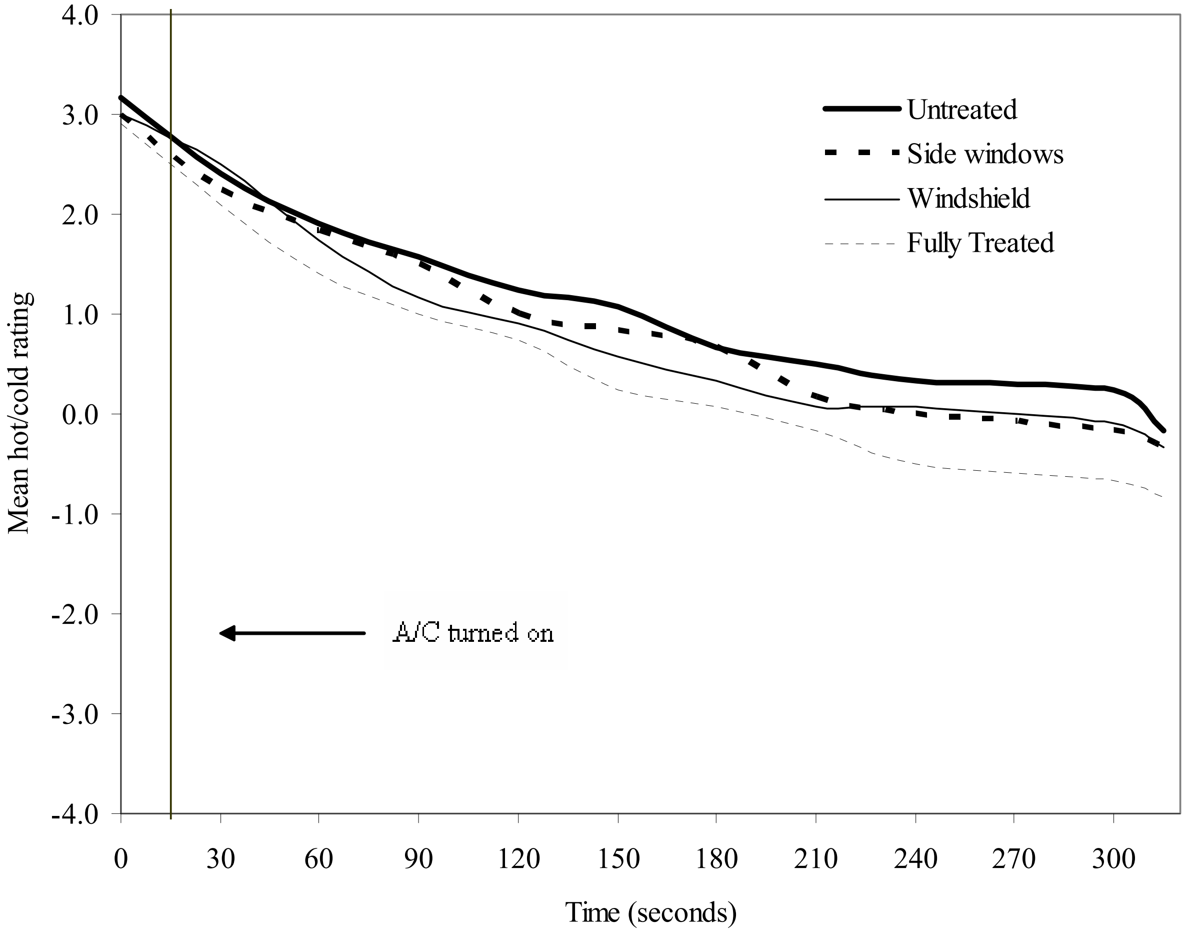

Figure 7. Hot/cold ratings as a function of time.

Thermal comfort

Tables 9 and 10 list the mean whole-body thermal comfort rating across all subjects for each level of the two independent variables.

Table 9
Comfort rating by IRR film placement
(0 = comfortable; 4 = extremely uncomfortable).

IRR film placement	Comfort rating
Fully treated	0.86
Windshield	0.90
Side windows	1.06
Untreated	1.13

Table 10
Comfort rating by A/C level
(0 = comfortable; 4 = extremely uncomfortable).

A/C level	Comfort rating
Maximum	0.82
High	1.15

A repeated measures analysis of variance was performed on comfort ratings that included two within-subjects variables (IRR film placement and A/C level) and two between-subjects variables (age and gender). The effect of IRR film placement was statistically significant, F(3, 24) = 3.259, $p < .05$. The marginal means (Table 9) followed the same overall pattern as the thermal sensation rating, skin temperature, and air temperature results.

The effect of A/C level was not significant, although average ratings were closer to "comfort" in the maximum A/C condition (Table 10), and the direction of the trend was as one might anticipate.

Finally, the effect of gender was significant, F(1, 8) = 12.181, $p < .01$. Males gave an average rating of 0.46, whereas females gave an average rating of 1.56. That is, females were on average less comfortable than males. Age had no effect on ratings of comfort.

Left and right forearms

Tables 11 and 12 list thermal sensation ratings in a similar manner as previous tables, except that Table 12 lists average ratings for the left versus right forearms. The ratings in Table 11 are collapsed across A/C levels and forearms, and the ratings in Table 12 are collapsed across A/C levels and IRR film placement.

Table 11
Hot/Cold rating by IRR film placement
(-4 = very cold; 0 = neutral; +4 = very hot).

IRR film placement	Hot/cold rating
Fully treated	0.60
Windshield	0.64
Side windows	0.91
Untreated	1.03

Table 12
Hot/Cold rating by forearm
(-4 = very cold; 0 = neutral; +4 = very hot).

Forearm	Hot/cold rating
Left	0.96
Right	0.63

A repeated measures analysis of variance was performed on thermal sensation ratings that included three within-subjects variables (IRR film placement, A/C level, and forearm) and two between-subjects variables (age and gender). Again, the effect of IRR film placement was significant, F(3, 24) = 4.6, $p < .05$. The effect of forearm was also significant, F(1, 8) = 7.2, $p < .05$. That is, subjects indicated that their left forearms felt hotter than their right forearms (Table 12).

The effect of A/C on forearm ratings was marginally nonsignificant ($p = .06$) and followed the same pattern as in previous analyses. Again, gender was significant, F(1, 8) = 5.6, $p < .05$, with females reporting hotter forearms than males. The mean rating for males was 0.09 and the mean rating for females was 1.50. There was no effect of age.

Time-to-comfort

Another way to examine how subjects rated their comfort is as a function of time. Tables 13 and 14 list the average amount of time that it took for the 12 subjects to reach a rating of "comfortable" for the different levels of the independent variables. Subjects reached comfort an average of 30 seconds earlier in the fully treated condition than in the untreated condition, and almost 44 seconds earlier in the maximum A/C condition than in the high A/C condition. Although these differences did not reach statistical significance, they illustrate the potential for treatments with stronger IRR rejection to have a significant effect on the time it takes to reach comfort. Finally, one difference that did reach statistical significance was gender. Females took an average of 2 minutes, 11 seconds longer to reach comfort than males, regardless of treatment condition, $F(1, 8) = 35.5, p < .01$.

Table 13
Time-to-comfort by IRR film placement.

IRR film placement	Time-to-comfort (seconds)
Fully treated	206.4
Windshield	217.8
Side windows	222.6
Untreated	236.4

Table 14
Time-to-comfort by A/C level.

A/C level	Time-to-comfort (seconds)
Maximum	198.6
High	242.4

Relationship between objective and subjective measures

One way to examine whether factors other than air temperature predicted how subjects rated their comfort is to look at a plot of air temperature versus subjective ratings. Figure 8 shows regression lines for thermal sensation ratings (averaged over 11 subjects due to missing data for one subject) as a function of mean air temperature and treatment condition. One can think of time as going from left to right in Figure 8, as the air temperature was the highest at the beginning of the trial (left) and decreased as the air conditioner was turned on (right).

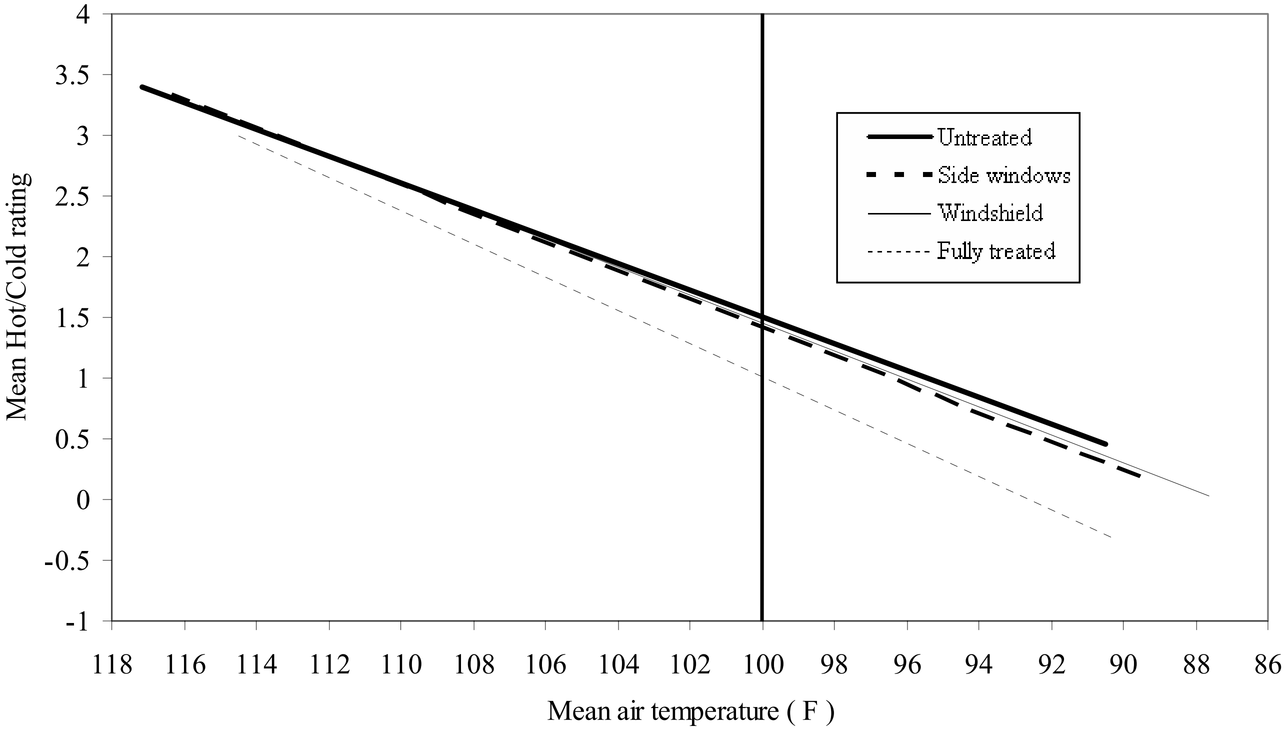

Figure 8. Hot/cold ratings as a function of air temperature and treatment condition.

One can see in Figure 8 how the fully treated car had an initially lower mean air temperature and mean hot/cold rating than the other conditions (upper-left corner). Similarly, one can see how the fully treated car did not cool down as rapidly as did the other conditions (lower-right corner). What is also evident from Figure 8, however, is that for any given air temperature throughout the course of the trial, ratings were lower for the fully treated condition than for any other condition.

For example, a paired-samples t-test was performed on the average rating between the fully treated and untreated conditions at 100° F. (This analysis used interpolated values based on regression equations for each subject.) The difference in ratings was significant, t(10) = -2.306, $p < .05$. The differences in subjective ratings (at any given air temperature) between the untreated condition and the windshield and side window conditions were not statistically significant, although one can see from Figure 8 that ratings were lower for the windshield and side window conditions. In other words, air temperature alone did not seem to account for differences in subjective ratings of thermal sensation.

When we examined ratings of thermal comfort, the same relationship was seen, although the magnitude of the difference between ratings at any given air temperature was smaller. This is illustrated in Figure 9, which shows the average comfort rating for each condition plotted as a function of air temperature and treatment condition.

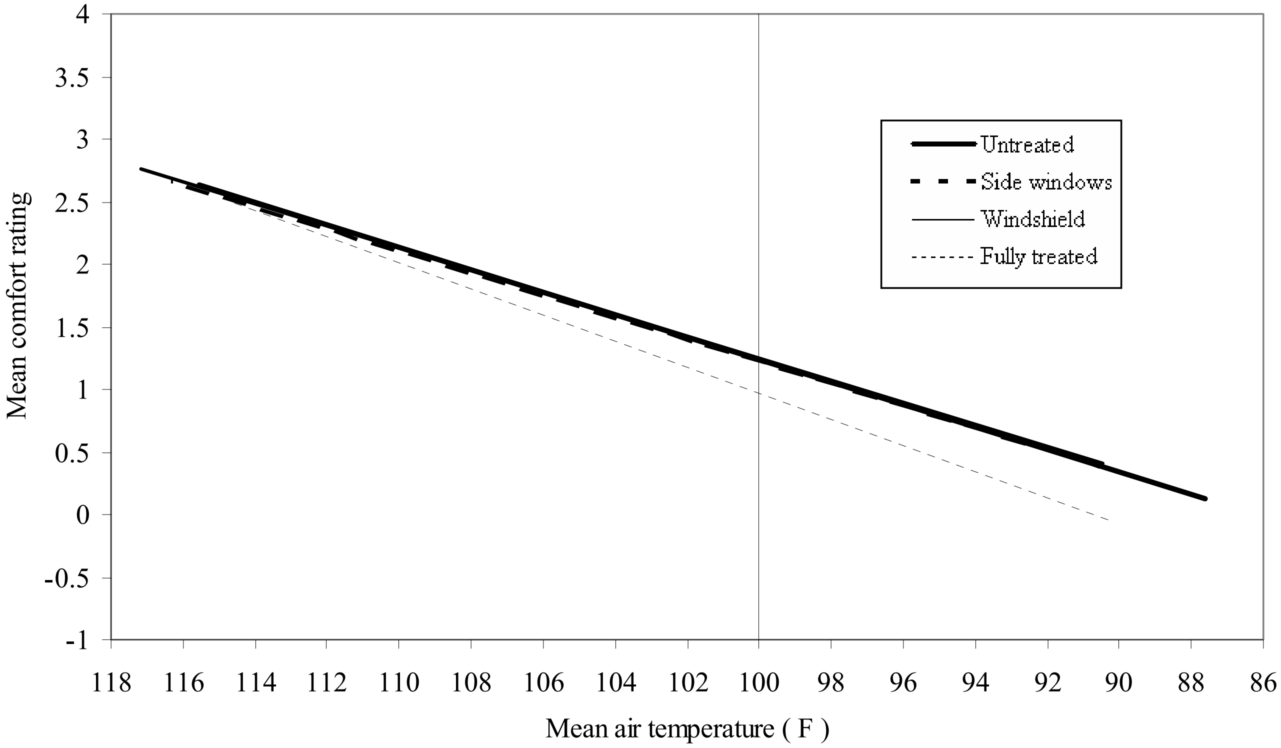

Figure 9. Thermal comfort ratings as a function of air temperature and treatment condition.

DISCUSSION

Mean skin temperature

Mean skin temperatures in the present study ranged from 34.1° C (fully treated condition) to 34.8° C (untreated condition). When compared to prior research (see, for example, Gagge, Stolwijk, & Hardy, 1967 (as cited in Parsons, 1993)), measurements in the present study appear consistent with what might be expected. It should be noted, however, that rate of perspiration has been shown to be a more accurate predictor of subjective ratings in hot environments than has skin temperature (Parsons, 1993). Nevertheless, the mean skin temperature differences observed in the present study give at least some evidence that ratings of thermal comfort were associated with physiological differences between experimental conditions.

Air temperature

On average, the IRR film reduced the air temperature inside the cabin. This is consistent with past research. The small magnitude of air temperature differences between experimental conditions (compared to differences typically found in other studies) most likely resulted from a combination of variable ambient weather and the relatively low IR rejection of the film. However, the air temperature was correlated not only with the amount of IRR film applied, but also with the mean skin temperature of the subjects.

Recall that the fully treated vehicle did not appear to cool down as rapidly as the other vehicles. One possible explanation for this is a difference in air conditioner output between the fully treated vehicle and the other vehicles. That is, the air from the A/C vents may not have been reaching the ceiling-mounted thermocouple in the fully treated vehicle.

Because mean skin temperature could have been affected by radiant heat, however, the higher air temperatures observed in the fully treated condition are not necessarily inconsistent with the lower skin temperatures and subjective ratings observed in that condition.

Subjective ratings

Ratings of thermal sensation and thermal comfort showed a strong relationship with the presence and amount of IRR film applied to the vehicle's glazing. At any given air temperature, ratings were better in the treated conditions than in the untreated condition. Because the purpose of IRR treatment is to reduce infrared radiation entering the vehicle, it seems plausible that the reduction in radiant heat associated with the treated conditions in turn affected subjective ratings of thermal sensation and comfort. Though this hypothesis is somewhat supported by the mean skin temperatures observed in the present study, a direct measure of radiant heat would have enabled a closer examination of the relationship.

Subjective ratings of thermal sensation on the forearms also supports the idea that radiant heat played a substantial role in thermal comfort. Subjects indicated that, on average, their left forearm felt hotter than their right forearm. Figure 11 illustrates why this may have been the case. The figure shows a typical example of the radiant heating distribution each subject experienced (when the sky was free from cloud cover). Note that the left side of the person's body is exposed to direct solar radiation while the right side of the body is not. Within the thermal comfort literature, this phenomenon is known as *radiant asymmetry*, and is a common cause of thermal discomfort.

Figure 11. Distribution of solar radiation within the vehicle cabin.

Future studies would benefit from incorporating direct measures of radiant asymmetry in order to examine how that parameter interacts with the air temperature distribution inside the vehicle cabin. Combined with measures of air velocity (around the A/C vents in particular), measures of radiant asymmetry could aid in a better understanding of the specific ways IRR treatment affects the environment inside vehicle cabins.

The consistent gender differences that were observed in subjective ratings of thermal sensation and comfort are also noteworthy. Females' ratings were generally much higher (i.e., hotter and more uncomfortable) than those of males. It is interesting to note, however, that there was no difference between males and females in the way that their ratings changed due to the IRR treatment. That is, ratings for both males and females decreased by the same degree when exposed to the IRR treatment conditions. However, the fact that females generally took longer to report a thermally comfortable state (regardless of the treatment condition) suggests that, for any given amount of IR rejection, males and females may not have similar ratings of comfort.

Limitations of this study

Baseline test

The present study did not use baseline measurements to examine any possible inherent differences between the four vehicles. Future studies would benefit from a series of baseline tests that are highly controlled for factors such as heating, ventilation, and cooling (HVAC) output, ambient weather, angle of the sun, and position of sensors. An example of such a procedure is outlined in Hymore, Tweady, and Wozniak (1991).

Other objective measures not collected

There were a number of objective measures that were originally part of the experimental design. They included solar irradiance through the driver's side window for each trial (measured via a pyranometer), dashboard surface temperature, skin temperature of subjects' right and left forearms, relative humidity, and "dry heat loss" (a measure that represents the combined effect of air temperature, mean radiant temperature, and air velocity).

These measures would have contributed to a more complete understanding of the climatic differences between experimental conditions. For example, measures of mean radiant temperature and solar irradiance would have provided a means of determining how radiant heat affected the subjects' ratings of comfort. In addition, such measures would have allowed a comparison between the empirical data collected from this study and existing models of thermal comfort (e.g., Fanger, 1970; Gagge, Stolwijk & Nishi, 1971).

Unfortunately, a series of technical problems rendered these measures unusable. Consequently, no reliable information was obtained on direct radiant heating of the skin. Such information would be necessary to directly test the hypothesis that IRR treatment has an effect on radiant heat that translates into increased occupant thermal comfort.

SUMMARY

An experiment was performed to determine how the application of an IRR treatment on a vehicle's glazing would affect objective measures of vehicle climate and subjective assessments of thermal sensation and comfort. It was found that the IRR treatment significantly reduced skin temperatures and air temperatures inside the vehicle cabin. In addition, subjective ratings were significantly different in the IRR treatment conditions versus the untreated condition. Subjects reached thermal comfort earlier and felt cooler when the IRR treatment was applied to the glazing. These effects were more pronounced as the surface area of IRR treatment increased.

It was also found that, at any given air temperature, subjects reported increased levels of comfort and thermal neutrality in the IRR treatment conditions. This implies that air temperature alone is not a complete predictor of thermal comfort. Although the study included no direct measurement of radiant heat, it is hypothesized that the ratings were influenced by the reduction in radiant heat associated with the IRR treatment.

The present study's main limitation was a lack of baseline data, which would have allowed a more thorough analysis of the experimental differences that were observed. Future studies should perform a series of highly controlled baseline tests, and should include a wide range of objective measures, such as air temperature, radiant temperature, relative humidity, and air velocity. With such measures, it would be easier to establish a relationship between thermal comfort and reduced radiant heat from IRR treatment.

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