Analyzing Thermal Comfort Distribution among Vehicle Occupants: Gender, Age, and BMI Effects

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SUMMARY

This study aimed to analyze the distribution of thermal comfort among vehicle occupants who experienced identical thermal sensations and to identify differences based on gender, age, and BMI. The study used an artificial chamber that simulated extreme summer and winter outdoor conditions, and participants provided feedback on their thermal sensation and comfort every 5 minutes during an actual vehicle evaluation. The results showed that males felt less comfortable than females with warm sensations under cooling conditions, and younger participants felt more comfortable with cold sensations under cooling conditions than older participants. These findings suggest that optimizing air conditioning environments for vehicle passengers requires considering individual physiological factors to achieve optimal thermal comfort and energy savings.

KEYWORDS

Thermal Sensation Vote(TSV), Thermal Comfort Vote(TCV), Vehicle environment, BMI, gender, age

1 INTRODUCTION

The rise of autonomous vehicles has increased the importance of investigating passengers' thermal comfort, as overcooling and overheating can negatively impact their health and energy consumption. Although most research on thermal comfort has focused on building environments, the indoor environment of a vehicle is highly dynamic, and the location of air conditioning outlets near local body parts can have a direct and indirect impact on passengers' thermal comfort (Chien et al., 2008). In addition, the Predicted Mean Vote (PMV) model, which is commonly used to predict thermal comfort based on the Predicted Percentage of Dissatisfied (PPD), was developed for uniform environments and may not accurately reflect the temporal and spatial characteristics of the vehicle environment. Therefore, a different approach is needed to investigate the thermal comfort of vehicle passengers.

There have been reports on the correlation between skin temperature and thermal sensation in the transient state of the indoor environment. For example, Zhou et al. (2019) conducted a survey response experiment in a moving vehicle and found a good correlation between mean skin temperature and overall thermal sensation of the human body. Additionally, in another study, it was found that the overall sensation was roughly a linear function of mean skin temperature when skin temperature was in the range between 29°C and 34°C. However, this relationship weakened as skin temperature went above or below the range (Zhang et al., 2009).

Although some studies have investigated the indoor environment and human responses in vehicles, previous studies tend to focus only on thermal sensation, and thermal comfort is considered to be one of the factors derived solely from thermal sensation, with the assumption that identical thermal sensation causes identical thermal comfort. Nonetheless, to provide an optimal environment for each driver or passenger, factors affecting thermal sensation and thermal comfort, except for thermal sensation itself, should be examined. Thus, we investigated how each subject's thermal comfort vote (TCV) differs when their thermal sensation votes (TSV) are the same. Additionally, we analyzed why these differences occur with regard to physiological parameters such as gender, age, and Body Mass Index (BMI).

2 MATERIALS/METHODS

2.1. Participants characteristics

Participants were recruited based on their gender and age, with men in their 20s and 30s, women in their 20s and 30s, and men in their 40s and 50s. During the experiments, participants' personal information, body indices, and their responses to the questionnaires about their thermal sensation and comfort status were collected.

2.2. Experimental environments

The experiment was conducted for 60 minutes inside a vehicle parked in an artificial climate room (see Figure 1), with two different environmental conditions: heating and cooling. For the cooling condition, the artificial climate room was set to an air temperature of 40°C and solar radiation of 830W/m2 to simulate a scorching summer outdoor environment. For the heating condition, the room was set to -20°C with no solar radiation to simulate the opposite. The experimental conditions of these two extremes were based on the seasonal temperatures in the Korean metropolitan area over the past 10 years (https://data.kma.go.kr).

The vehicle's indoor temperature was initially set to the same temperature as the artificial room with doors opened. Once the participants boarded the vehicle and the doors were closed, the cooling/heating system was started in the 23°C Auto mode, where the temperature and humidity were automatically adjusted to reach the target temperature of 23°C. Participants were not allowed to autonomously operate the air conditioning mode.

2.3. Experiment procedures

Upon arrival at the experimental site, participants changed into experimental clothing with a clothing value of 0.55clo and 0.78clo for heating and cooling conditions, respectively. Participants' height was recorded in advance, and their BMI was calculated by measuring their weight and body fat rate during the experiment. Participants waited for 30 minutes in a preconditioned room with a PMV value set between -0.5 and 0.5 to stabilize their bodies, and then they stayed in the vehicle for 60 minutes to conduct a subjective evaluation of their thermal sensation and comfort.

2.4. Measurement

The subjective evaluation was conducted 13 times at 5-minute intervals immediately after boarding. Unlike general buildings, vehicles have a wider temperature range in the indoor environment and rapidly change over time, so the scale used in previous studies on vehicle thermal comfort was adopted. The scales (Figure 2) are divided into -4 to +4, which indicate very cold to very hot for thermal sensation and very uncomfortable to very comfortable for thermal comfort. After all experiments were completed, the indoor environment was measured once using the Automotive HVAC Manikin System (Thermetrics, USA). Indoor air temperature, thermal radiation, air velocity, and relative humidity data were collected every 5 seconds.

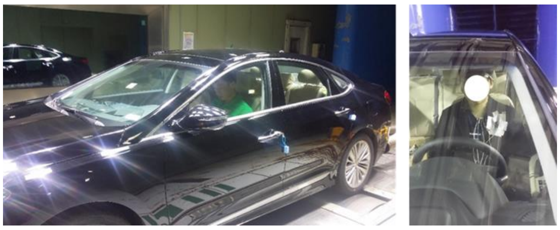


Figure 1. Experimental settings.

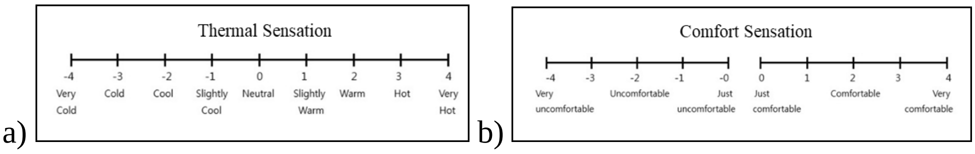


Figure 2. Subjective evaluation scales. a) Thermal Sensation Vote, b) Thermal Comfort Vote.

Table 1. Measuring instruments

Name of the instrument	Parameters(unit)	Accuracy
Automotive HVAC Manikin System	Air Temperature (°C)	±1.0 °C calibrated accuracy ±0.1 °C resolution
	Air Velocity (m/sec)	±0.05 m/sec (0.1-1.0 m/sec) ±0.1 m/sec (1.1-5.0 m/sec)
	Thermal Radiation ($W/m^{2)}$	±100 W/m^2
	Relative Humidity (%)	±5 % calibrated accuracy
TSK 7+1	Skin Temperature (°C)	±0.1 °C calibrated accuracy
Inbody 370S	Weight (Kg)	

3 RESULTS

3.1. Thermal comfort distribution

The valid data obtained was 40(24 males and 16 females)and 46(28 males and 18 females) for heating and cooling conditions, respectively. The indoor air temperature and the humidity of the vehicle increased/decreased and then stabilized at 27°C, 4%RH for heating conditions and decreased/increased and then stabilized at 28°C, 23%RH for cooling conditions.

3.1.1. Heating conditions

In the case of heating, within the first 15 minutes of boarding the vehicle, all subjects had a TSV lower than 0, and at least 75% of them voted -2 or less for TCV, indicating discomfort due to the cold sensations.

As shown in Figure 3-a, after 20 minutes, the number of subjects who voted 0 for thermal sensation continued to increase, and 23 out of 40 subjects felt neither hot nor cold about the thermal environment at the end of the experiment. Among them, none experienced cold or warm discomfort, and half of the participants voted 0 or 2 for their TCVs, 30% and 20% for each value. The proportion of subjects who had a neutral thermal sensation (TSV=0) and a comfortable feeling (TCV≥2) concurrently also increased over time, as shown in Figure 3-b. This result suggests that not only the neutral thermal environment itself but also the duration of the environment can affect thermal comfort.

When the 60-minute in-car experiments finished with a stabilized indoor environment, although the number of participants whose thermal sensation moved from cold to neutral increased, less than 40% of them felt comfortable. Moreover, none answered with 4 (very comfortable), and only 2 participants answered with 3 for the thermal comfort vote, indicating that a neutral thermal sensation alone cannot confirm whether the occupant is very comfortable.

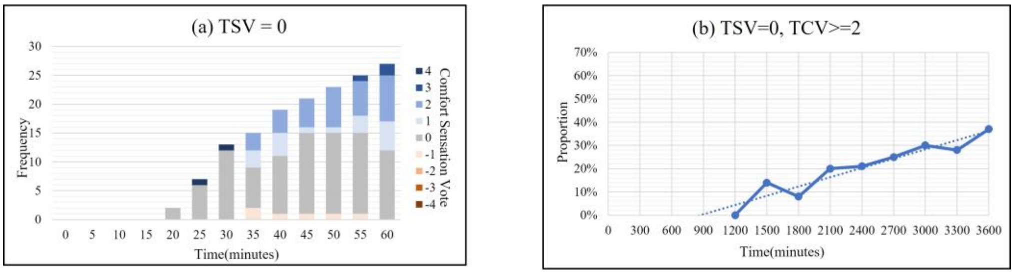


Figure 3. Frequency and ratio of Thermal Comfort Vote to Thermal Sensation Vote

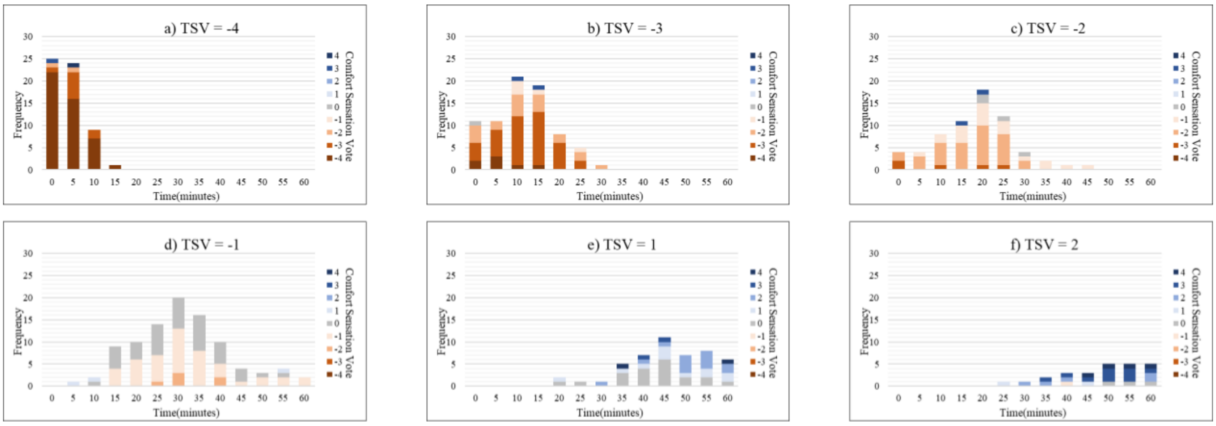


Figure 4. TCV distribution for identical thermal sensation.

The participants who responded with a TSV of -1 for thermal sensation increased until 30 minutes after boarding and then gradually decreased. The corresponding thermal comfort for this sensation varied from -2 to 2, as shown in Figure 4-d. In the middle of the experiment, where the frequency of the corresponding thermal sensation was more than ten times, at least 40% of the subjects felt slightly uncomfortable (TCV≤-1), which is similar to the proportion of subjects who felt just fine (TCV=0).

The number of participants who responded with TSV values of 1 or 2 (Figure 4-e,f) for thermal sensation was much smaller than that of other thermal sensation values, and there were no participants who felt uncomfortable among them, unlike for TSV=-1. Most of the participants who answered their TSV as -4 or -3 (Figure 4-a,b) existed only for the early phase of the experiment, and they felt uncomfortable with TCV≤-2, and none of them had a TSV of

3 or 4. These results indicate that when participants feel extreme thermal sensations, their thermal comfort tends to be concentrated at one point. Moving to a moderate sensation alleviates that tendency, with comfort votes dispersing to various TCV points.

3.1.2. Cooling conditions

Unlike the heating conditions, none of the participants voted for negative values for thermal sensation as soon as they boarded the vehicle. Instead, 24%, 37%, 26%, and 7% of the participants were distributed in the thermal sensation values of 1, 2, 3, and 4, respectively. After that, there were no cases where the TSV was 3 or more, and the number of participants who voted 2 for thermal sensation was less than 5 over the entire experiment.

Throughout the experiment, at least 20 out of 46 participants voted 0 for thermal sensation, meaning that more than half of the participants felt a neutral thermal sensation for all time except for the very early stage of the experiment when the air temperature was 40°C. On the other hand, the ratio of participants who voted 2 or more for thermal comfort among those whose thermal sensation vote was 0, which means that they felt comfortable because of neutral thermal sensation, had increased. This tendency was the same as that discovered in the heating conditions. However, there was also a difference in heating conditions. More than half of the participants answered that it was neither comfortable nor uncomfortable, and only 38% responded with a thermal comfort vote value of 2 or more, which was marked as comfortable. That ratio for cooling conditions reached about 60%, as shown in Figure 5. This result suggests that HVAC mode could be an influencing factor in participants' thermal comfort.

Figure 6 shows the TCV distributions for TSV 1 and -1, indicating that the number of participants who voted 1 or -1 were similar. The overall proportion belonging to all comfort statuses, including TCV 1,2, which are light blue colors, was higher when TSV was 1 than when it was -1. However, the proportion of the very comfortable status, including TCV 3,4, darker blue colors, was hardly any and lower when TSV was -1 than when it was 1.

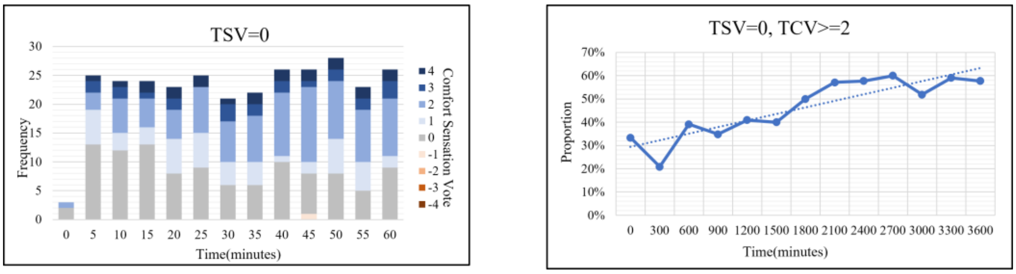


Figure 5. Frequency and ratio of Thermal Comfort Vote to Thermal Sensation Vote

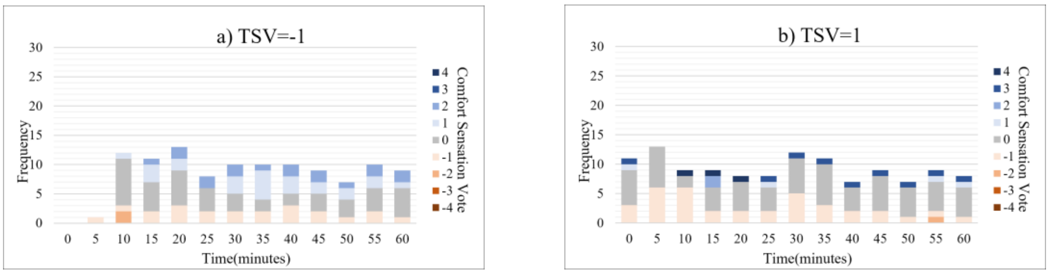


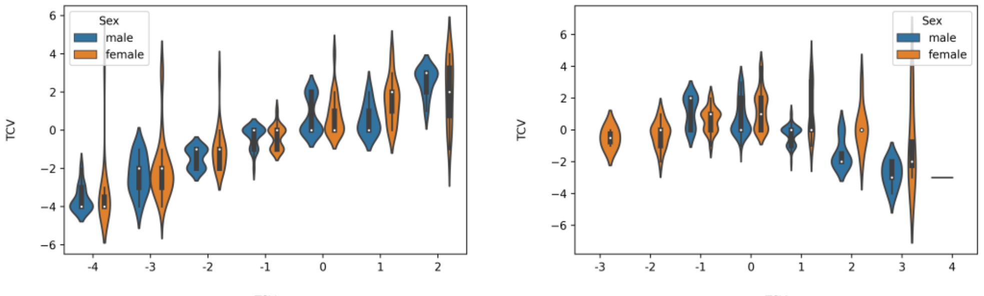
Figure 6. TCV distribution for identical TSV

3.2. Comparison of thermal comfort vote values for identical thermal sensation

3.2.1. Gender

In order to control for the influence of age, data from male and female participants in their 20s and 30s was analyzed, while excluding participants in their 40s and 50s. Figure 7a shows the results for heating conditions, while Figure 7b shows the results for cooling conditions.

For heating conditions, the average TCV values for the two groups were similar, indicating that gender may not be a significant factor that affects the difference in TCV for the same TSV. However, for cooling conditions, the male group had a lower TCV for the same TSV, except for TSV=-1, which corresponds to a cold sensation. This suggests that men felt less comfortable with warm sensations under cooling conditions compared to women.

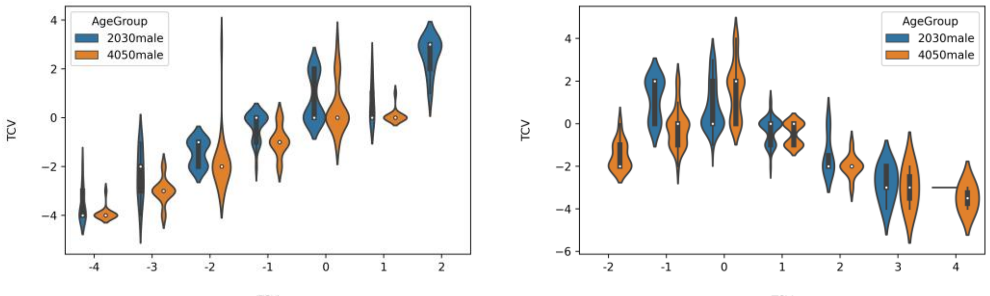


a) b)

Figure 7. Gender difference in TCVs for identical TSVs for each condition. a)heating condition, b)cooling condition.

3.2.2. Age

In order to exclude the influence of gender, data from male participants in their 20s and 30s and in their 40s and 50s were used to explore the age difference, excluding female participants. Figure 8 shows TCVs for two age groups for the same TSV. In the case of heating conditions, the younger group felt more comfortable than the older group with cold sensation, while in the case of cooling conditions, a specific trend could not be confirmed.



a) b)

Figure 8. Age difference in TCVs for identical TSVs for each condition. a)heating condition, b)cooling condition.

3.2.3. BMI

According to WHO standards, individuals are classified into four groups based on their body mass index (BMI), which includes underweight (BMI<18.5), normal weight (18.5≤BMI<25), overweight (25≤BMI<30), and obese (BMI≥30). In this study, participants were divided into two groups: those with a BMI between 18.5 and 25 and those with a BMI of 25 or higher. One participant from the underweight group was excluded from the analysis since there was only one participant in this group for both heating and cooling conditions.

Table 2. Number of samples by group

Group	Heating conditions	Cooling conditions
Normal	24	28
Overweight	15	17
Total	39	45

Due to insufficient sample size for TSV values of -4, -3, -2, 2, 3, and 4, a comparison of average TCV was only carried out for TSV values of -1, 0, and 1. Figures 9 and 10 show the comparison results for heating and cooling conditions, respectively. No graphs were created for the time periods without samples. For example, in the case of graph a) in Figure 9, no participant in the Normal group responded with a TSV value of 1 until 10 minutes had passed.

In both conditions, there was a general tendency for the Overweight group to feel less comfortable than the Normal group under any TSV conditions, except for the late 15 minutes of cooling conditions when participants felt a neutral thermal sensation. Furthermore, when participants had a neutral thermal sensation in heating conditions, the TCV values of both groups converged toward a TCV value of 1, which is a comfortable stage, during the last 15 minutes of the experiment. A similar tendency was observed in cooling conditions, where participants felt a cold sensation, and the gap between groups became smaller entering the latest part of the experiment, converging to a TCV value of 0.25. However, the gap between groups was substantial when participating in a cooling experiment, with a maximum difference of 2, as shown in Figures 10-a and 10-c.

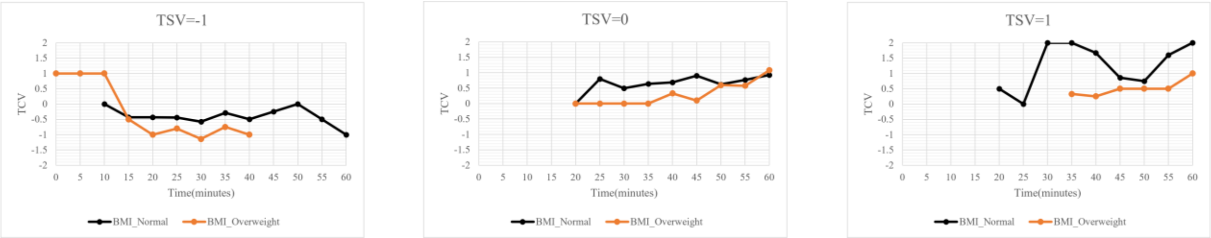


Figure 9. Comparison of TCVs when TSV is -1,0,1 by BMI groups in heating conditions

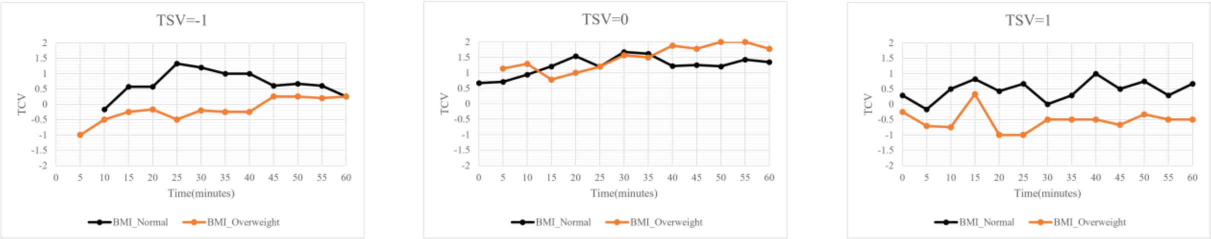


Figure 10. Comparison of TCVs when TSV is -1,0,1 by BMI groups in cooling conditions

4 DISCUSSION

In Section 3.1.1 and Section 3.1.2, the proportion of participants who reported a TCV of 0 or 2 far exceeded the other TCV values. This may be due to the thermal comfort scale used in our experiment, where captions were only provided above the points of -4, -2, 0-, 0+, 2, and 4.

This tendency can be seen in the same context as the research by Buratti et al. (2016). They investigated occupants' thermal comfort using two different thermal sensation scales: a 7-point ASHRAE scale and a 13-point scale subdivided into 0.5. The results showed that the proportion of people who declared a neutral thermal sensation using the new 13-value scale decreased significantly from 66% to 41% for classrooms and from 47% to 36% for theater auditoriums. Therefore, future studies should use a subdivided scale to prevent the phenomenon of not reflecting the actual comfort status and concentrating only on points with a caption.

There are some previous studies concerning BMI differences in thermal comfort. For example, Rupp et al. (2018) found that the not overweight group was more likely to express "cold" discomfort, and Indraganti et al. (2015) found that women, young subjects, and those with lower BMI index had a higher comfort temperature than men, older adults, and obese people. Nevertheless, in Section 3.2.3, the result that the overweight group had lower comfort than the normal-weight group under cold and warm sensations does not accord with those results. This is because this study analyzed TCV corresponding to thermal sensation, not temperature itself, and the number of subjects was focused on the normal group by recruiting with upper and lower limits on the BMI level at the initial subject recruitment.

5 CONCLUSIONS

This research investigates thermal comfort in an actual vehicle environment with non-uniform and transient characteristics. Unlike other studies, this research focuses on the distribution of individuals' thermal comfort for identical thermal sensations. The study reveals that not only the neutral environment itself but also the duration of maintaining the neutral environment can affect thermal comfort. Moreover, even if the neutral environment is continuously maintained, a high percentage of participants find it neither pleasant nor unpleasant.

The research also shows that HVAC conditions with different initial air temperatures affect participants' thermal comfort, and the influence of gender and age factors differs between cooling and heating conditions. The findings suggest that thermal sensation alone may not reflect thermal comfort status accurately. To provide an optimized and energy-saving thermal environment, it is crucial to investigate the factors that influence thermal comfort through thorough and fine-grained group comparisons.

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