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MATLAB 기반 열심리 가시화 기법

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A MATLAB-based Approach for Visualization of Human Thermal Psychology

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Abstract Effective thermal management in a battery electric vehicle (BEV) is crucial for reducing energy consumption and maximizing driving range in cold climates. Consequently, original equipment manufacturers are actively investing in the development of local heating systems. Visualizing occupant thermal behaviors or comfort can readily provide valuable insights that would substantially impact the design and control strategies of such microclimate systems. This study uses MATLAB for three-dimensional visualization of human thermal psychology. The developed program enables qualitative assessment of occupant comfort in BEVs.

Key Words : Visualization, MATLAB, Thermal psychology, Electric vehicle, Thermal management, Local radiant heating

1. Introduction

Thermal psychology entails the study of how individuals perceive and respond to their thermal surroundings, and it plays a vital role in shaping human behavior and well-being. In recent years, significant attempts[1–6] have been made to improve our understanding of human thermal psychology by emphasizing its relevance in various aspects of daily life, both indoors and outdoors. Personal comfort systems (PCSs) have been introduced in response to the substantial energy consumption required to maintain indoor thermal comfort[7]. Such systems provide localized heating or cooling to improve occupant comfort while conserving energy[8,9]. PCSs hold promise for occupant-centric winter conditioning, encouraging the use of battery electric vehicles (BEVs) in regions with harsh winter climates[10]. However, the development of efficient and tailored heating solutions for BEVs lacks a foundation grounded in human thermal psychology[11].

Human perception of the thermal environment

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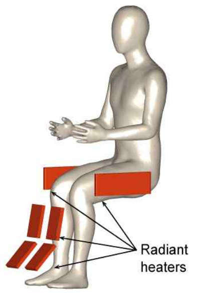
involves two key semantic dimensions: thermal sensation and comfort[12]. Thermal sensation refers to objective assessment of the thermal surroundings, whereas comfort is associated with hedonic or affective description. It has been reported that the skin temperature determines thermal sensation, which in turn mediates human thermo-regulation[13,14]. Thermoregulatory responses, such as peripheral vasodilation and vasoconstriction, are triggered when there are disparities between the current physiological state and thermoneutral state[15]. Humans perceive comfort or discomfort in cold or warm environments when the corresponding sensations mediate these thermoregulatory behaviors. This characteristic of thermal sensation that elicits comfort or discomfort is known as *thermal alliesthesia*[16–18]. Zhang et al.[4,19,20] and Parkinson and de Dear[21,22] have respectively observed that temporal and spatial changes in sensation can induce temporal and spatial thermal alliesthesia. Moreover, the overall comfort experienced by an individual is determined through the integration of local comfort values, although the exact mechanisms involved remain unclear[23]. The framework of thermal alliesthesia can be applied to develop effective winter conditioning systems in BEVs. Some previous studies[10,24,25,26] have demonstrated that integrating local radiant heating systems with conventional cabin heating, ventilation, and air conditioning (HVAC) systems can improve occupant satisfaction while reducing energy consumption in cold climates. Nonetheless, the design of such systems necessitates careful consideration and attention. While radar, bar, or line plots are frequently utilized for monitoring occupant thermal comfort, visualizing these data on 3D models offers notable advantages. Firstly, it enables a more holistic and intuitive understanding of the relationship between thermal stimuli and human perception. Secondly, by representing thermal comfort information on a 3D model, areas of potential discomfort can be easily identified. Moreover, visualizing thermal comfort empowers designers and researchers to assess the impact of various design interventions or strategies on thermal comfort. However, a simple and cost-effective visualization tool for qualitative assessment of occupant comfort has not been reported before.

This work presents a MATLAB-based program to visualize thermal sensation and comfort data on a 3D human model. The program utilizes data obtained from a previous experimental study investigating the efficacy of local radiant heaters on occupant comfort in typical BEVs operating in cold climates[26]. The primary objective of this work is to highlight the importance of visualizing thermal psychology and its relevance to the design of occupant-centric heating systems in BEVs.

2. Methods

The thermal physiological data used in this study for visualization were obtained from our previous investigation[26] that involved participation of 25 healthy young Korean men of average weight 71.5 ± 7.4 kg, height 175.5 ± 5.5 cm, and age 22 ± 3 years.

In our previous study, Yoon et al.[26] provided a thorough description of the experimental methodology. The study aimed to gather thermal perception data within a real BEV setting, simulated under winter conditions (−10 °C) in an environmental chamber. Two distinct experimental designs, referred to as cases A and B, were implemented to investigate the effects of different heating scenarios. In case A, the cabin HVAC system was actively utilized with a setpoint temperature of 25 °C. Conversely, in case B, the same HVAC system was augmented by a set of local radiant warmers (LRWs) positioned around the lower bodies of the occupants, with a surface temperature of 90 °C. The experimental observation was limited to a duration of 40 mins. The schematic of LRW setup and details of heating conditions are illustrated in Fig. 1.



Heating condition	Description	Duration
Case A	HVAC (25 °C) only	40 mins
Case B	HVAC (25 °C) + Radiant heaters (surface temperature of 90 °C)	

Fig. 1. Schematic of the local radiant warmer (shown in orange red) configuration, and heating scenarios reported by Yoon et al.[26]. The human model is from the *Size Korea*[27] platform.

2.1 Skin temperature and perception data

Yoon et al.[26] measured the skin temperatures at specific positions on the body using wireless sensors (iButtons, DS1925/1922L, Maxim Integrated, San Jose, CA, USA). The authors employed a 7-point scale[2] ranging from *"very uncomfortable"* (−3) to *"very comfortable"* (+3) to collect the thermal comfort data. Additionally, a 9-point scale[4] was used to record the thermal sensation votes ranging from *"very cold"* (−4) to *"very hot"* (+4) by considering cold cabin conditions prior to the experiment. The participants rated their local sensations (for 10 different body parts), overall sensation, local comfort (for the upper and lower bodies), and overall comfort on these scales every 3 min, with a resolution of half a scale unit. Figures 2a and 2b depict the scales used to collect the perception votes. The average skin temperatures and perception votes of the 25 subjects from the two warming cases were used in this visualization study.

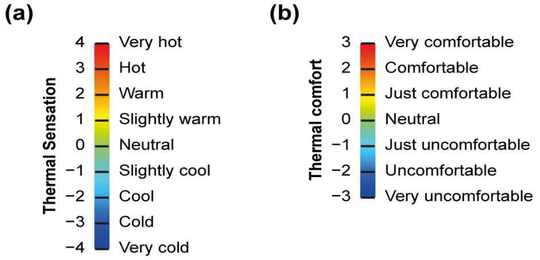


Fig. 2. Thermal perception scales used for (a) sensation and (b) comfort voting.

2.2 Human model and data visualization

A realistic 3D human model representative of the typical participant was obtained from the *Size Korea*[27] platform. The model used in this study did not include clothing. Using the modeling software Blender, the model was remeshed and divided into 10 distinct body parts: head, chest, back, pelvis, right/left upper arm, right/left lower arm, right/left hand, right/left thigh, right/left leg, and right/left foot. This segmentation was done to map the local perception vote for each body part separately.

A MATALB program developed in-house was used to visualize the thermal perceptions on the human model. MATLAB offers very powerful 3D visualization capabilities; it also supports various file formats for the 3D models. The MATLAB environment does not import the model but rather reads the geometric information and creates a representation of the model in memory. This representation typically includes the vertices (points) and faces (triangles) that form the surfaces of the 3D model. Once the model is read, its properties may be accessed or manipulated.

In this study, STL files of the segmented model parts were used to prepare the 3D geometrical data for subsequent manipulation and visualization within the MATLAB environment. The MATLAB package "stlread"[28] was employed to read the STL files and extract the mesh faces and vertices. The extracted information was then organized and connected to ensure consistent and efficient manipulation of the 3D geometrical data. The built-in MATLAB function “trisurf” was used to generate a surface plot with triangles connecting the vertices based on the connectivity information. We used linear interpolation to establish the relationship between plot color and perception votes. Appropriate lighting effects were also incorporated to retain the 3D appearance of the model. The program would consistently produce reliable visualizations without the necessity for additional accuracy verification measures, given the integrity of the data.

3. Results and Discussion

The following sections present and discuss the average skin temperatures and perception votes that have been linearly interpolated at time intervals of 0, 10, 20, 30, and 40 min for the two warming scenarios. These data points are visualized on the 3D human model. Yoon et al.[26] maintained the same pre-cabin conditions to ensure consistency throughout the experimental sessions. Further, it was reported that both cases of cabin heating showed similar variations in the cabin air temperature, with subjects showing no significant drop in their core temperature.

3.1 Local skin temperature

Figures 3 and A1 depict the temporal variations of the local skin temperatures during the experimental observations under the two modes of warming. The skin temperature was assumed to be influenced solely by the cabin HVAC system and LRWs surrounding the lower body, as there was no significant decline in the core temperature observed during the experiment. Despite the subjects being acclimatized to the cold conditions in the beginning under identical cabin ambience, their skin temperatures exhibited variations across different body parts, ranging

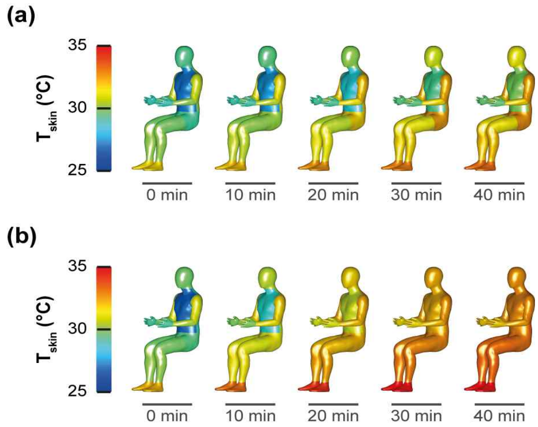


Fig. 3. Variations in local skin temperatures (T_{skin}) of participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min. Note that the skin temperatures at 10 distinct locations have been visualized, with the exception of the back area, which is not visible in this representation.

from 26.7 °C to 32.2 °C. These variations were attributed to the differential skin thickness, thermal conductivity, and thermal capacity[29].

At 0 min, under both A and B cases, the data demonstrate comparable distributions of the skin temperatures. The chest area exhibits a relatively lower skin temperature (26.8 °C), while the face, back, pelvis, hand, and thigh areas display slightly higher skin temperatures in the range of 29.1 °C to 29.9 °C. Conversely, the upper arm, lower arm, leg, and foot exhibit higher skin temperatures, ranging from 30.2 °C to 31.9 °C. Over the course of 40 min under case A, notable increases in skin temperature were observed in specific body regions. The chest, back, and pelvis demonstrated higher increments of 3.1 °C, 2.3 °C, and 3.4 °C, respectively, while the skin temperature of the lower body parts displayed a smaller increment of 1.6 °C. In contrast, under case B, the effects of local radiant heating of the lower body parts were apparent, as they showed a higher skin temperature change of 3.3 °C. However, the skin temperature of the upper body also increased as a result. This observation is intriguing considering the similar cabin conditions reported for both cases A and B, which leads us to suspect that peripheral blood perfusion may affect the skin temperature.

3.2 Local and overall thermal sensation

Figures 4 and A2 illustrate the variations in the local thermal sensations for cases A and B at time steps of 0, 10, 20, 30, and 40 min. At 0 min, all body parts exhibited *"cool to very cold"* sensations, with notable coolness observed in the hand, thigh, leg, and foot regions.

Despite the lower skin temperature in the chest area, the lower body parts experience colder sensations. The effects of local warming on the lower body become noticeable after 10 min, as evidenced by the sensation in the thigh region under case B. Although the legs experience relatively higher changes in skin temperature, they are the least affected body parts in terms of thermal sensation. These findings align with the observations that the lower body extremities exhibit lower sensitivity to warming, as reported by Luo et al.[29].

Although local radiant warming was directed toward the lower body parts, the upper body parts

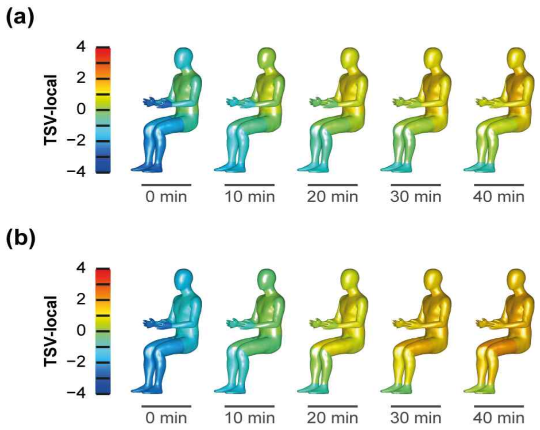


Fig. 4. Variations in local thermal sensations (TSV-local) of the participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

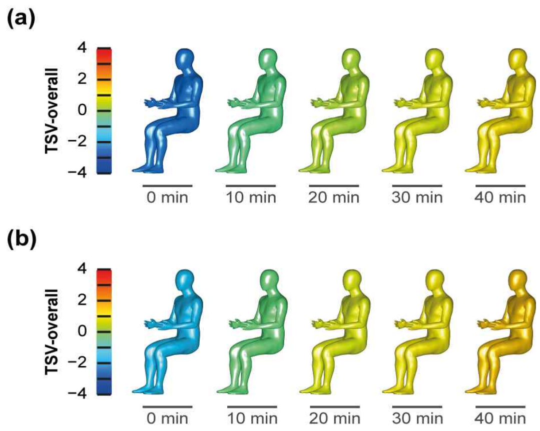


Fig. 5. Variations in overall thermal sensations (TSV-overall) of the participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

also experienced increased sensations of warmth. This may be because of the influence of blood perfusion, as mentioned in the previous section. Figures 5 and A2 depict the variations in the overall thermal sensations for both cases at the same time intervals. This offers valuable insights into the process by which the human brain integrates local sensations to determine overall values. Initially, at 0 min, the overall sensation is determined by the local cold sensation in body areas such as the hand, thigh, leg, and foot (−2.5). This pattern persists for up to 10 min regardless of warming cases; thereafter, under case A, the thermal sensation in the upper body area contributes to the overall sensation, whereas under case B, the sensation in the thigh region contributes significantly. Furthermore, as the subject was brought to room temperature, the overall thermal sensation overshot to "*slightly warm to warm*." The observed overshoot in thermal sensation is more pronounced in case B; this can be attributed to the fact that the subjects were acclimatized to cold conditions prior to the experiments, and the greater increase in skin temperature led to a greater overshoot in the perception of warmth[12,30].

3.3 Local and overall thermal comfort

Figures 6, 7 and A3 visualize the temporal variations in the local and overall thermal comfort levels reported by the participants under cases A and B at time steps of 0, 10, 20, 30, and 40 min. The lower body parts are in obvious discomfort at 0 min. This is because of the thermoregulatory load error (i.e., thermal stress) in response to the cold sensation[31].

The local radiant heating does not modify the thermal comfort of the lower body until 20 min,

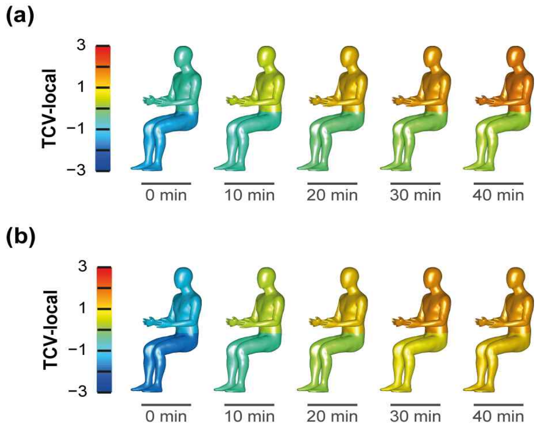


Fig. 6. Variations in local thermal comfort (TCV-local) levels of participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

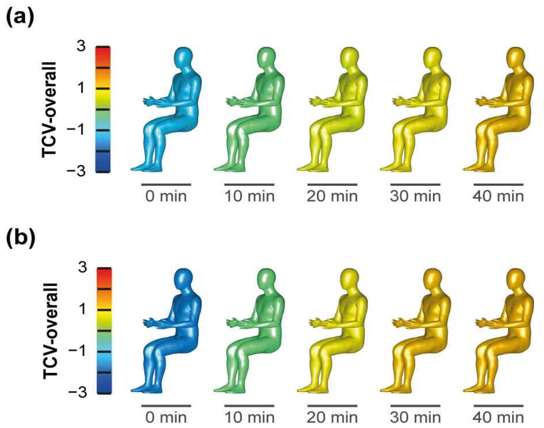


Fig. 7. Variations in overall thermal comfort (TCV-overall) levels of the participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

which aligns with the observations regarding local sensations. It can be inferred that the perception of comfort closely follows the sensations experienced by an individual as they transit from cold to warm environments. The local heating of the lower body improves local comfort because the application of warmth in cold alleviates thermal stress[23]. On the other hand, under cold conditions, the extreme local discomfort significantly influences the overall thermal comfort, as reported by Zhang et al.[20].

The overall comfort after 20 min is no longer attributable to the extremely comfortable body parts but rather an approximate of the average local comfort. Therefore, overall occupant comfort improves with the application of local heating. At 30 min, the overall comfort under case B is noticeably higher than that under case A. However, by 40 min, the overall comfort levels are similar in both cases; this suggests that the greater overshoot in sensation observed under case B may have caused the subjects to perceive a lower change in comfort. The authors speculate that if the duration of exposure were extended beyond 40 min, a decrease in thermal comfort might be observed earlier under case B than case A.

From a theoretical standpoint, the overshoot in thermal sensation presents the opportunity to reduce the cabin HVAC setpoint, thereby potentially reducing energy consumption. Additionally, occupant comfort may be maximized and maintained through effective control of their overall sensation in response to the change in thermal preference. In this regard, local radiant heating systems emerge as a promising approach for occupant-centric comfort control in future BEVs.

3.4 Limitations

Our program is not designed for real-time quantitative monitoring purposes; it is specifically developed to visualize post-experimental thermal perception data to draw meaningful insights. By integrating the program with a data entry application or psychological model[32], real-time visualization of thermal psychology may be achieved. It is of significance to emphasize that our approach does not provide statistical information regarding the impact of local heating. Furthermore, the discussion in this study is limited owing to the consideration of a number of time steps (n = 5).

4. Conclusions

The present study entails the development of a MATLAB-based tool for visualizing human thermal comfort aimed at assessing the effects of local radiant heating. We employed this tool to visualize experimental data that captured occupant perceptions within BEVs under two distinct cabin heating scenarios: conventional HVAC alone and conventional HVAC combined with localized heating. The approach provides qualitative assessments of occupant sensation and comfort and investigates the integration of local perception votes into overall values. Furthermore, results show that humans are likely to perceive higher comfort levels with local heating systems. Overall, our findings underscore the effective application of the developed program for analyzing post-experimental thermal perception data among different heating scenarios. In the context of designing occupant-centric heating systems for BEVs, this program has the potential to significantly advance our understanding of thermal perception in dynamic environments.

Acknowledgments

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REFERENCES

1) Fanger, P. O. and Toftum, J., 2002, "Extension of the PMV Model to Non-Air-Conditioned Buildings in Warm Climates," Energy and Buildings, Vol. 34(6), pp.533～536.

2) Yeon, S. H., Lee, H. J., and Rhee, G. H., 2016, "The Study on the Effect of the Solar Radiation on Thermal Comfort and Ventilation Performance in Room Space," Journal of the Korean Society of Visualization, Vol. 14(1), pp.19～26.

3) Arens, E., Zhang, H., and Huizenga, C., 2006, "Partial- and Whole-body Thermal Sensation and Comfort—Part II: Non-uniform Environmental Conditions," Journal of Thermal Biology, Vol. 31(1-2), pp.60～66.

4) Zhang, H., Arens, E., Huizenga, C., and Han, T., 2010, "Thermal Sensation and Comfort Models for Non-Uniform and Transient Environments: Part I: Local Sensation of Individual Body Parts," Building and Environment, Vol. 45(2), pp.380～388.

5) Parkinson, T. and de Dear, R., 2015, "Thermal Pleasure in Built Environments: Physiology of Alliesthesia," Building Research & Information, Vol. 43(3), pp.288～301.

6) Liu, S., Nazarian, N., Hart, M. A., Niu, J., Xie, Y., and de Dear, R., 2021, "Dynamic Thermal Pleasure in Outdoor Environments - Temporal Alliesthesia," Science of the Total Environment, Vol. 771, p.144910.

7) He, Y., Parkinson, T., Arens, E., Zhang, H., Li, N., Peng, J., Elson, J., and Maranville, C., 2022, "Creating Alliesthesia in Cool Environments Using Personal Comfort Systems," Building and Environment, Vol. 209, p.108642.

8) Zhang, H., Arens, E., and Zhai, Y., 2015, "A

Review of the Corrective Power of Personal Comfort Systems in Non-Neutral Ambient Environments," Building and Environment, Vol. 91, pp.15～41.

9) Zhang, H., Arens, E., Taub, M., Dickerhoff, D., Bauman, F., Fountain, M., Pasut, W., Fannon, D., Zhai, Y., and Pigman, M., 2015, "Using Footwarmers in Offices for Thermal Comfort and Energy Savings," Energy and Buildings, Vol. 104, pp.233～243.

10) Tiwari, A., Varandani, V., Mandali, S., and Arsenault, J., 2022, "Design of a Human-Centric Auto-Climate Control System for Electric Vehicles," SAE International Journal of Advances and Current Practices in Mobility, Vol. 5(2022-01-0194), pp.748～761.

11) Kwon, J. Y., Kim, J. K., Lee, H., Lee, D., and Ju, D. Y., 2023, "A Comprehensive Overview of Basic Research on Human Thermal Management in Future Mobility: Considerations, Challenges, and Methods," Sustainability, Vol. 15(9), p.7335.

12) Vellei, M., de Dear, R., Inard, C., and Jay, O., 2021, "Dynamic Thermal Perception: A Review and Agenda for Future Experimental Research," Building and Environment, Vol. 205, p.108269.

13) Marks, L. E., Gonzalez, R. R., and Gonzalez, R. R., 1974, "Skin Temperature Modifies the Pleasantness of Thermal Stimuli," Nature, Vol. 247(5441), pp.473～475.

14) Nagashima, K., Tokizawa, K., and Marui, S., 2018, "Thermal Comfort," Handbook of Clinical Neurology, Vol. 156, pp.249～260.

15) Romanovsky, A. A., 2018, "The Thermoregulation System and How It Works," Handbook of Clinical Neurology, Vol. 156, pp.3～43.

16) Cabanac, M., 1971, "Physiological Role of Pleasure," Science, Vol. 173(4002), pp.1103～1107.

17) Cabanac, M., 1979, "Sensory Pleasure," The Quarterly Review of Biology, Vol. 54(1), pp.1～29.

18) Cabanac, M., 1988, "Alliesthesia," Sensory Systems: II, pp.1～1.

19) Zhang, H., Arens, E., Huizenga, C., and Han, T., 2010, "Thermal Sensation and Comfort Models for Non-Uniform and Transient Environments, Part II: Local Comfort of Individual Body Parts," Building and Environment, Vol. 45(2), pp.389～398.

20) Zhang, H., Arens, E., Huizenga, C., and Han, T., 2010, "Thermal Sensation and Comfort Models for Non-Uniform and Transient Environments, Part III: Whole-Body Sensation and Comfort," Building and Environment, Vol. 45(2), pp.399～410.

21) Parkinson, T. and de Dear, R., 2016, "Thermal Pleasure in Built Environments: Spatial Alliesthesia from Contact Heating," Building Research & Information, Vol. 44(3), pp.248～262.

22) Parkinson, T. and de Dear, R., 2017, "Thermal Pleasure in Built Environments: Spatial Alliesthesia from Air Movement," Building Research & Information, Vol. 45(3), pp.320～335.

23) Arens, E., Zhang, and H., Huizenga, C., 2006, "Partial- and Whole-Body Thermal Sensation and Comfort— Part I: Uniform Environmental Conditions," Journal of Thermal Biology, Vol. 31(1), pp.53～59.

24) Kang, B. H., and Lee, H. J., 2017, "A Review of Recent Research on Automotive HVAC Systems for EVs," International Journal of Air-Conditioning and Refrigeration, Vol. 25(04), p.1730003.

25) Lee, Y., Lee, H., Kang, B. H., and Kim, J. K., 2021, "Machine Learning-Based Personal Thermal Comfort Model for Electric Vehicles with Local Infrared Radiant Warmers," Journal of Mechanical Science and Technology, Vol. 35(7), pp.3239～3247.

26) Yoon, S. E., Gopi, G., Fakhrulrezza, M., Lee, H., and Kim, J. K., 2023, "Measurement and Prediction of Thermal Comfort of Occupants in Electric Vehicle under Dynamic Local Radiant Heating Conditions," Transactions of the Korean Society of Automotive Engineers, Vol. 31(7),

pp.479～491.
27) Kim, J. Y., You, J. W., and Kim, M. S., 2017, “South Korean Anthropometric Data and Survey Methodology: ‘Size Korea’ Project,” Ergonomics, Vol. 60(11), pp.1586～1596.
28) Harlev, D., 2023, “Stlread,” MATLAB Central File Exchange.
29) Luo, M., Wang, Z., Zhang, H., Arens, E., Filingeri, D., Jin, L., Ghahramani, A., Chen, W., He, Y., and Si, B., 2020, “High-Density Thermal Sensitivity Maps of the Human Body,” Building and Environment, Vol. 167, p.106435.
30) Rankin, C. H., Abrams, T. W., Barry, R. J., Bhatnagar, S., Clayton, D. F., Colombo, J., Coppola, G., Geyer, M. A., Glanzman, D. L., Marsland, S., McSweeney, F. K., Wilson, D. A., Wu, C. F., and Thompson, R. F., 2009, “Habituation Revisited: An Updated and Revised Description of the Behavioral Characteristics of Habituation,” Neurobiology of Learning and Memory, Vol. 92(2), pp.135～138.
31) Gagge, A. P., Stolwijk, J. A. J., and Hardy, J. D., 1967, “Comfort and Thermal Sensations and Associated Physiological Responses at Various Ambient Temperatures,” Environmental Research, Vol. 1(1), pp.1～20.
32) Prasad, B., Lee, Y., Kang, B. H., Kim, J. K., and Lee, H., 2019, “Development of a Thermal Physiological Model to Analyze the Effect of Local Radiant Heaters in Electric Vehicles,” Journal of Mechanical Science and Technology, Vol. 33(7), pp.3577～3584.

Appendix

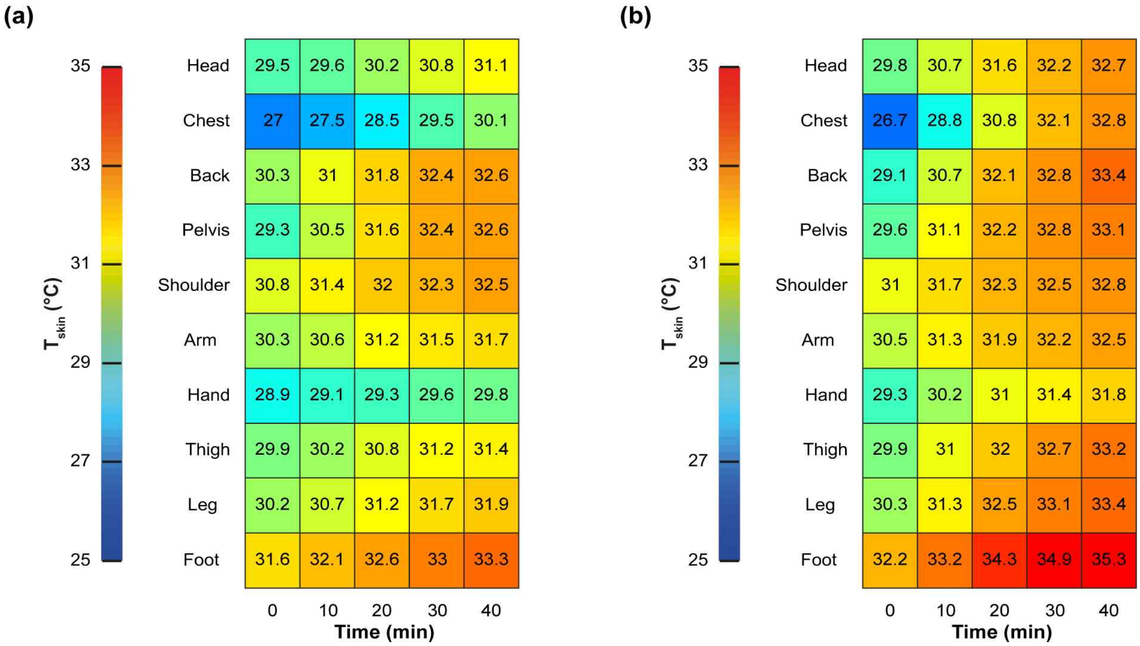

Fig. A1. Heatmap representation of the local skin temperatures (T_{skin}) of participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

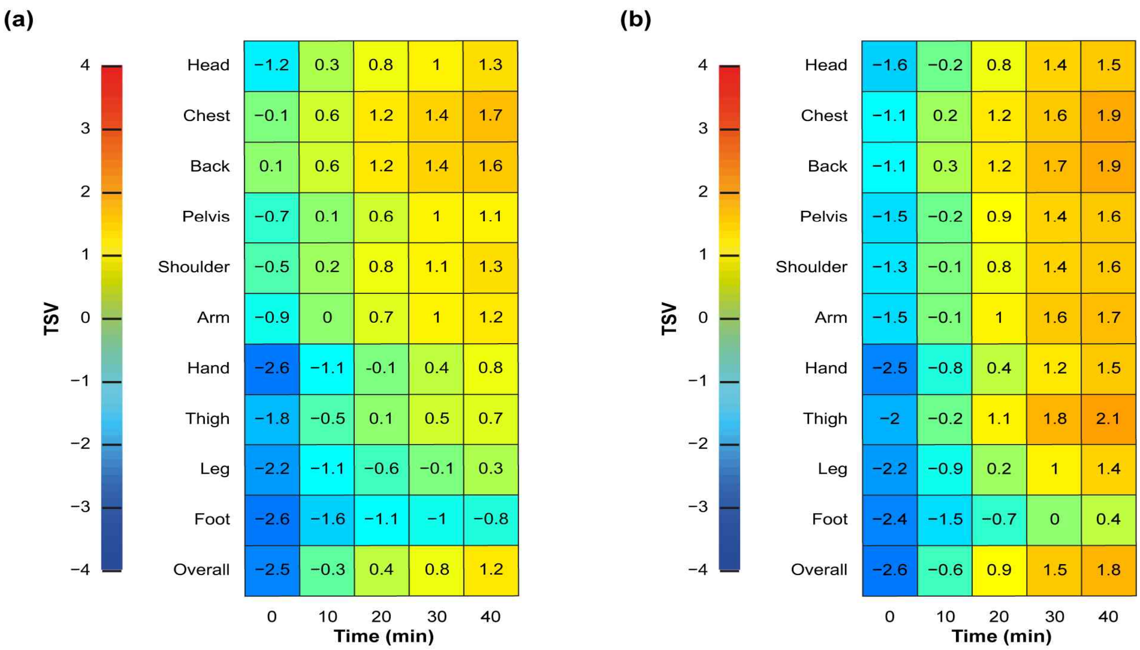

Fig. A2. Heatmap representation of the local and overall sensation (TSV) of participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min.

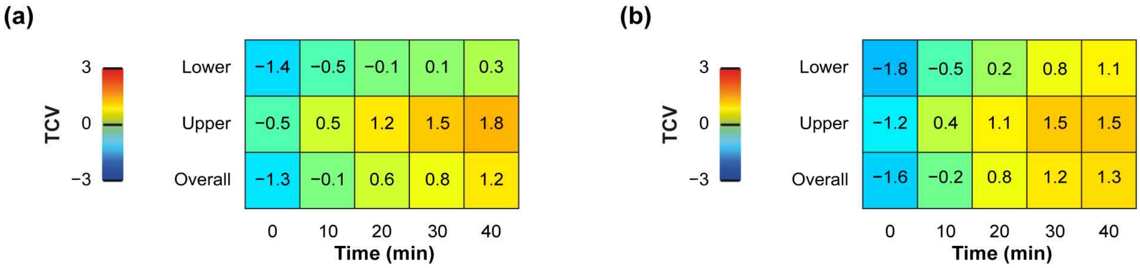

Fig. A3. Heatmap representation of the local and overall comfort (TCV) of participants for cases (a) A and (b) B at discrete time steps of 0, 10, 20, 30, and 40 min