



HAL
open science

Berkeley thermal comfort models: Comparison to people votes and indications for user-centric HVAC strategies in car cabins

Rachelle Abou Jaoude, Ilango Thiagalingam, Roch El Khoury, Gabriel Crehan

► To cite this version:

Rachelle Abou Jaoude, Ilango Thiagalingam, Roch El Khoury, Gabriel Crehan. Berkeley thermal comfort models: Comparison to people votes and indications for user-centric HVAC strategies in car cabins. *Building and Environment*, 2020, 180, pp.107093 -. 10.1016/j.buildenv.2020.107093 . hal-03491172

HAL Id: hal-03491172

<https://hal.science/hal-03491172>

Submitted on 15 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Berkeley thermal comfort models: comparison to people votes and indications for user-centric HVAC strategies in car cabins

Rachelle Abou Jaoude³, Ilango Thiagalingam¹, Roch El Khoury¹

Gabriel Crehan²

¹Vedecom, 23 bis allée des Marronniers, 78000 Versailles,
France

²PSA Group, Technical center of Vélizy A, Route de Gisy,
78140 Vélizy-Villacoublay, France

³MINES ParisTech, PSL Research University, Center for
energy Efficiency of Systems, 5 Rue Léon Blum, Palaiseau,
91120, France

June 19, 2020

Abstract

New heating and cooling strategies can be adopted in a smart way to bring thermal comfort while reducing energy requirements. UCB thermal sensation and comfort models can be viewed as an alternative to the PMV standard to investigate frugal and local strategies for namely electric vehicles. In the present investigation, people votes are recorded while they were experiencing transient and quasi-homogeneous scenarios in cool and warm automotive-like environments and compared to the UCB Zhang model predictions. Quite good qualitative agreements are found between model predictions and actual votes particularly in warm environments. On the strength of these results, a parametric investigation is carried out and interesting

trends about thermal preferences are brought to light for each body part. It is observed that body parts have, depending on the global thermal ambiance, different expectations in terms of thermal preferences. For instance, one can mention that the pelvis should only be cooled slightly even in extreme hot environments, otherwise the comfort is strongly deteriorated. Based on this investigation body parts that have to be focused in priority have been identified for different global thermal ambiances (very cold $So = -4$, cold $So = -2$, neutral $So = 0$, warm $So = 2$ and very hot $So = 4$) and suggestions for comfort-oriented and energy saving-oriented strategies have been proposed.

1 Introduction

The automotive industry is today at the beginning of a historic turning point as the mobility concept is going through a paradigm shift. The political pressure to reduce local pollution led automotive manufacturers to replace the fleet composed of vehicles with an internal combustion engine by electric vehicles[1]. In this respect, today's strategies to bring thermal comfort have to be fully reviewed as the power used to bring thermal comfort directly impacts the autonomy of electric vehicles[2]. Thermal comfort research has been recently reactivated to find technological solutions in order to bring the highest quality of thermal comfort inside cabins with the lowest level of energy use[3, 4, 5, 6, 7, 8].

The European EN ISO 14505[9, 10, 11] and the American ASHRAE-55 [12] are the current standards proposing methods for the thermal comfort evaluation in car cabin environments. In these standards, thermal comfort indices employ the equivalent temperature concept which can be used in heterogeneous but steady environments[13, 14, 15] and the PMV (Predicted Mean Vote)-PPD (Predicted Percentage of Dissatisfied) approach introduced by Fanger[16] which unfortunately has been intended particularly for homogeneous and steady environments inside buildings.

Automotive environments set apart from building environments by the tight and confined space in which passengers are constrained to stay seated for a relatively long period of time. And contrary to building environments, cabin environments mainly evidence high transient and non-homogeneous thermal conditions [17, 18, 19]. This specificity is explained principally by

the use of air conditioners and the impact of solar radiation. Effectively, the level of the convective heat transfer between the human body and its surroundings is driven by air velocities and temperature differences. In automotive environments, due to the orientation of aerators, their relative closeness to the driver and passengers and heterogeneous speed and temperature set-points of the blown air at the aerators' outlet (for instance in actual vehicles and in winter conditions, the air blown in feet compartments is warmer than the air blown from aerators located on the upper side of the dashboard) the operating air conditioning system generates heterogeneous air temperature around the body. Besides, certain body parts experience large radiative heat exchanges under summer outdoor conditions because of the directionality of the direct short-wave solar radiation. In addition, the non-uniformity of interior wall temperatures (use of radiating panels for instance) could lead to a non-uniform long-wave radiation field around the human body. Conductive heat exchange with the seat (heating or ventilated active seats) could be another source of non-uniformity in automotive environment. Furthermore, unlike air-conditioned buildings, the in-cabin climate is dominated by transient thermal conditions as more than 85% of trips involve an average distance fewer than 18 km, with a duration of 15 to 30 min[20]. Thus, it was shown in [21] that thermal comfort study should be conducted under transient conditions in car cabins as thermal conditions remain transient in most of the situations.

As the PMV indices were established based on a steady-state heat transfer between the human body and the homogeneous surrounding environment, it does not provide accurate predictions for automotive environments. Effectively, it was pointed out for instance that the overall percentage of dissatisfied was higher than the PPD obtained with the Fanger's model for the same overall thermal sensation vote when the thermal non-uniformity exceeded a certain level. It implies that a non-uniform thermal environment increases the occupants' overall percentage of dissatisfied [22]. Moreover, the European EN ISO 14505 and the American ASHRAE-55 standards are based on environmental parameters and do not request a thermophysiological model describing the thermal response of the human body to external thermal solicitations. Thus, they may provide acceptable predictions in steady state conditions but they are not intended to model the comfort perception in unsteady environmental conditions[23]. The inertia effect, active and passive thermo-regulation mechanisms of the human body to restore the thermal equilibrium between the body and the environment have a significant impact

in the transient perception of thermal sensation[24, 25]. The need to include these transient effect is highlighted for instance by the DTS (Dynamic Thermal Sensation) model[26]. In order to capture accurately transient physiological and psychological effects on the thermal comfort perception, a fine modelling of the interaction between the unsteady thermal environment and the human thermal system is required. In this respect, a refined multi-node model for thermal comfort which fits to the current imperatives can be seen as a substitute to the PMV indices[27, 28, 29, 30]. Comfort models proposed by Zhang [31, 32, 33, 34] and based on thermophysiological parameters are shown to be convenient to predict human perception of comfort in heterogeneous and unsteady environmental conditions. With such models, the local impact of transient and heterogeneous thermal stress can be fully accounted and used to spot local discomfort so that the HVAC system could be intended to bring satisfaction on those particular body parts. In this paper, it is proposed to investigate experimentally the applicability of the local thermal comfort model of Zhang in transient and quasi-homogeneous automotive environment and suggest indications to properly set the HVAC system. The present experimental investigation will mainly focus on the evaluation of the Zhang model to predict the perception of local and global comforts in unsteady environmental conditions.

In the following sections, the experimental set up is first presented. Cool and warm transient scenarios are investigated and thermal sensation and comfort votes of a panel of human subjects are recorded. Those votes are then compared to the UCB Zhang thermal comfort model predictions. Finally a parametric study is carried out with the UCB Zhang thermal comfort model to draw main qualitative trends between local and global sensations and comforts in order to come up with indications to set an user-centric HVAC system that either satisfy the occupants thermal needs at best or either bring the minimum comfort while reducing the energy use.

2 Experimental set up

2.1 Description of the test bench

A thermal test bench that represents a B-segment car cabin is used for the experimental investigation (Fig.1). The cabin interior volume is $2.9 m^3$. The internal walls of the test cell are covered with 42 independent flat stainless

steel heat exchangers reproducing the car cabin geometry. Their temperatures can be controlled from 5 to 45°C using ten independent water-glycol circulation circuits. An air handling unit provides control over the mass flow rate, temperature, and humidity of the air that is injected into the cabin. Several temperature probes monitor surface as well as air temperatures throughout the test (see Fig.2). Other environmental parameters such as black globe temperature, air humidity, and airflow velocities are also measured around the tester. The human test subjects that underwent thermal exposures are provided with identical and thermally characterized clothes (T-shirt+legging+shoes resulting in a clo of 0.38) for the experiments. Each tester went through the following exposure:

- 30 minutes of sedentary preconditioning at 25°C in a separate room
- 90 or 180 minutes of test with the tester seated in the driver seat inside the test bench experiencing a transient quasi-homogeneous scenario

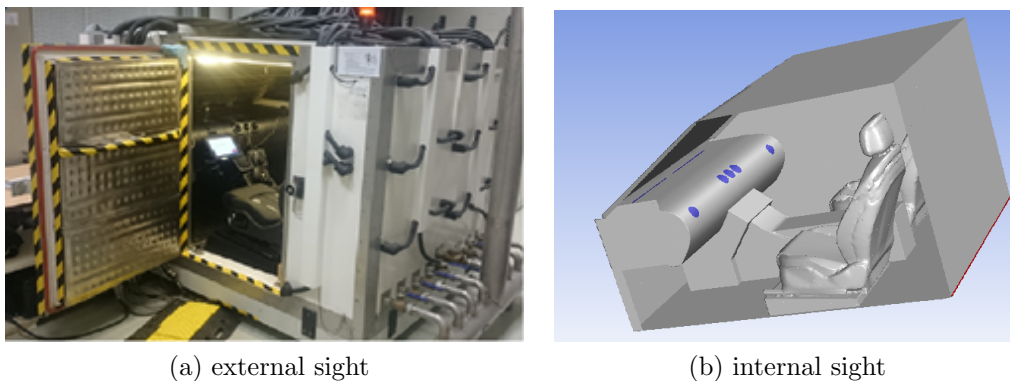


Figure 1: The test bench

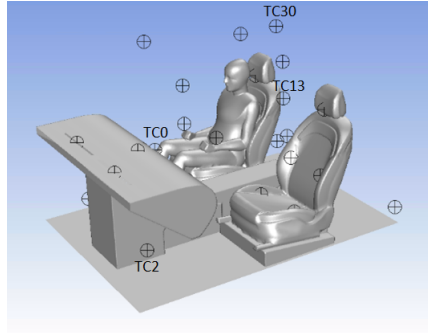


Figure 2: Location of the thermal sensors inside the cabin

Throughout the test, airflow and humidity from the air handling unit are fixed to $250m^3/h$ and 50% respectively. Air is injected into the cabin through aerators. There are three aerators at the center of the dashboard, one on left and right side corners, two others are below the wind shield (Fig.1) and two below the dashboard near the driver and front passenger feet. All temperature sensors are calibrated using a standard Pt100 thermometer with an accuracy of $0.2^\circ C$. During tests, the environmental conditions are continuously recorded at an interval of 10 seconds. Thermal sensation and comfort votes are collected at a five-minute interval and the Zhang nine-point scale is used for the votes.

2.2 Test scenarios

2.2.1 Description

Scenarios have been designed to bring the human body from the comfort zone (preconditioning at $25^\circ C$ before entering in the test bench or walls and air temperature setpoint maintained at $25^\circ C$) to a discomfort zone (cool or warm) and then bring it back to the comfort zone. The investigated scenarios are the followings:

- Test A: injected air and panel temperatures set at $45^\circ C$ for 30 minutes and afterwards switched abruptly to $25^\circ C$ for an additional 60 minutes. Number of human subjects: 10.
- Test B: injected air and panel temperatures set at $25^\circ C$ for 60 minutes, switched to $15^\circ C$ abruptly for an additional 60 minutes and reset to $25^\circ C$ for another 60 minutes. Number of human subjects: 5.

- Test C: injected air and panel temperatures set at $25^{\circ}C$ for 60 minutes, switched abruptly to $35^{\circ}C$ for 60 minutes and reset to $25^{\circ}C$ for another 60 minutes. Number of human subjects: 6.

A number of at least eight human subjects by scenario is recommended [11] in thermal comfort experimental investigation. We observed that this number could be reduced to a minimum of five human subjects to capture the qualitative mean trend of sensation and comfort votes as most individual signals are dampened making the mean vote curve and the standard deviation band noiseless.

2.2.2 Validation

To make sure that human subjects are experiencing nearly the same thermal environment, it is checked that measured temperatures on the panels or at the aerator nozzles are effectively the given temperature instructions. Fig.3 shows for instance that for the test scenario C, there is a very good agreement between the temperature of the fifth water-glycol circulation circuit (B5 for loop or Buckle number 5) regulating among others the panel number five and the temperature on the panel number five (P5 for Panel number 5).

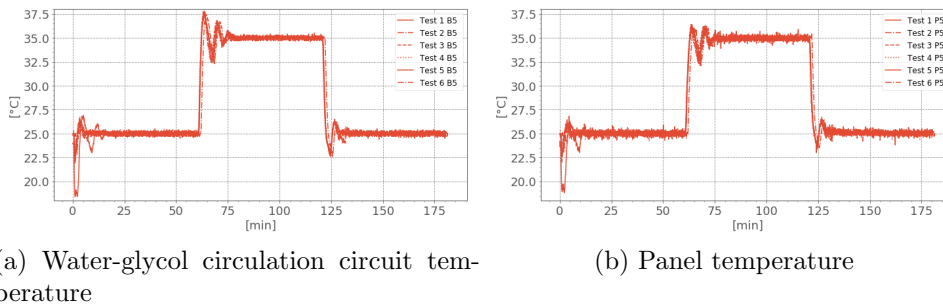


Figure 3: Temperature profiles on the panel 5 and on its corresponding water-glycol circulation circuit for the test scenario C

A very good agreement between the six tests is found as well. Likewise, during the test scenario B for instance, it is observed a good match between the temperature at the central aerator nozzle (TC0 in Fig.2) and the air handling unit loop (Fig.4).

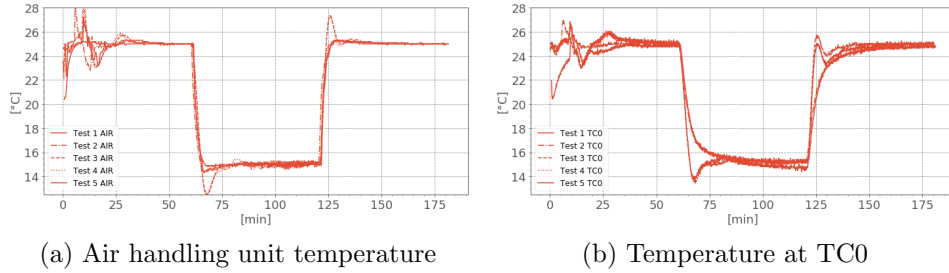


Figure 4: Temperature profiles recorded on TC0 and in the air handling unit loop

A very good agreement can be also observed between tests apart in the very transient part. Fig.5 and Fig.6 show that standard deviations represented by box plots and calculated on each panel and aerator are very low. Mostly, they are lower than $0.5^{\circ}C$ on panels and lower than $1.5^{\circ}C$ for blown air temperatures, despite the fact that the local deviation can be quite large (it can reach nearly $3.5^{\circ}C$).

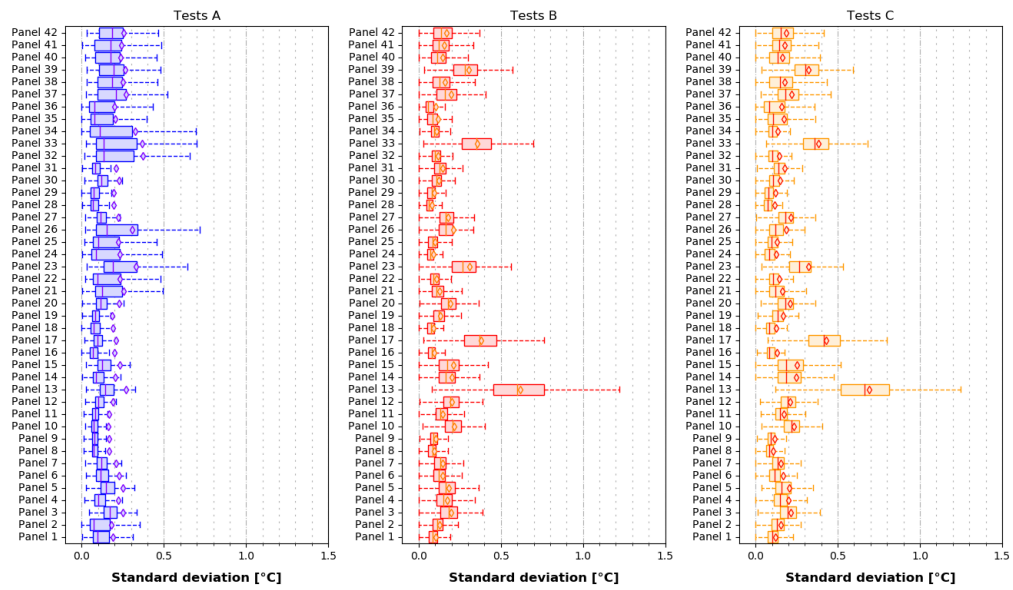


Figure 5: Box plots of panels temperature RMSD for test scenario A, B and C. The diamond represents the mean value.

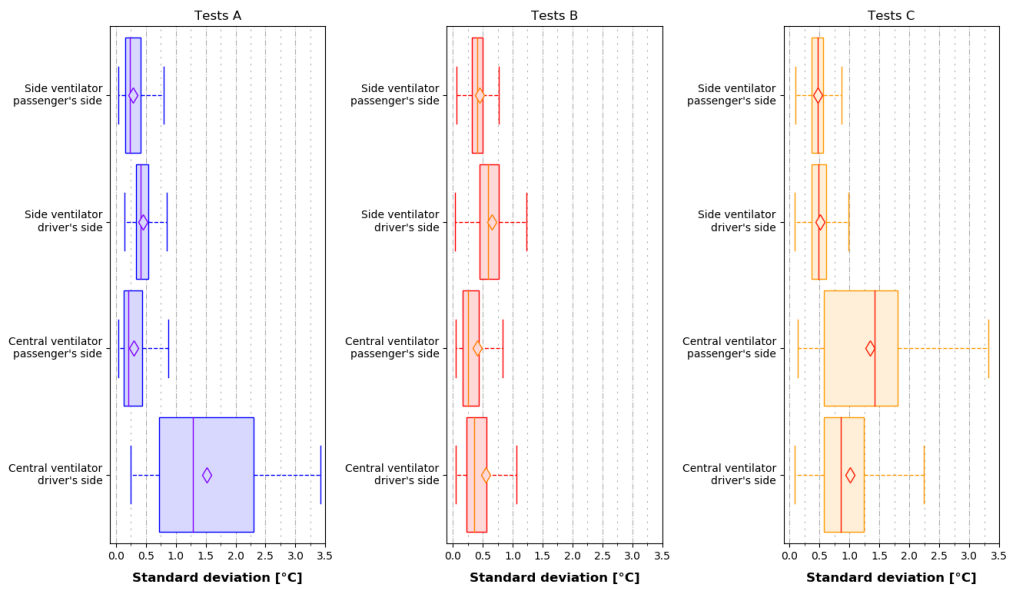


Figure 6: Box plots of aerators temperature RMSD for test scenario A, B and C. The diamond represents the mean value.

The temperature on thermocouple 13 (see Fig.2) located at the midpoint between the driver and the passenger seats at 40 cm from the roof shows that the general thermal environment is comparable for all testers. However discrepancies of around $1^{\circ}C$ can be found in the stationary part whereas they can reach $2^{\circ}C$ to $4^{\circ}C$ in the very transient part (see Fig.7).

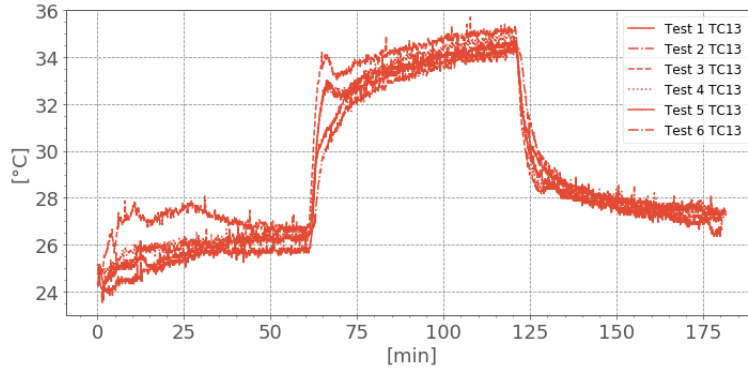


Figure 7: Temperature profiles measured by the sensor TC13 during the test scenario C

UCB Zhang local comfort models prediction ability in transient situations is investigated in this study. Thus, the thermal environment is intended to keep homogeneous by setting all panels and blown air temperature set-points identical and by blowing through aerators an air at a high flow rate ($250m^3/h$). Despite this, the thermal stress experienced by testers is neither homogeneous nor very heterogeneous (high thermal asymmetry). Effectively, as can be seen in Fig.8, for the test scenario B, there are noticeable differences between temperatures measured by the probe TC30 which is located at the midpoint between the driver and the passenger at 12 cm from the roof and the one located driver side below the dashboard and above the foot pedals (TC2 in Fig.2). For instance at $t = 120$ min, the probe TC2 reaches $16^{\circ}C$ whereas the probe TC30 measures a temperature around $18.5^{\circ}C$. Thus, the thermal environment experienced by human subjects is considered to be transient and quasi-homogeneous.

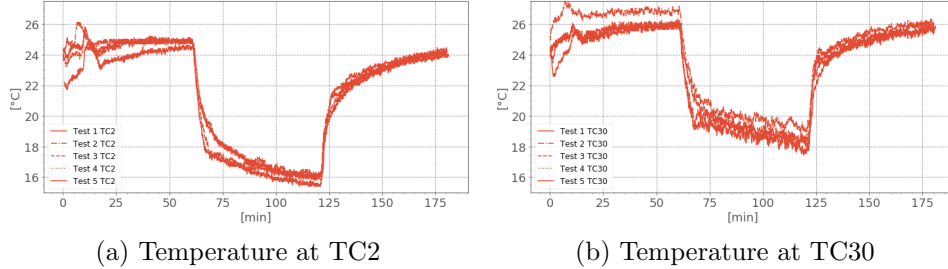


Figure 8: Temperature profiles measured by TC2 and TC30 during the test scenario B

3 Results and discussion

3.1 Comparison of the Zhang sensation and comfort models with people votes in automotive environment

In 2003, Zhang [31] developed predictive models for local and overall thermal sensations and comforts in non-uniform and transient conditions whereas most thermal comfort models such as the PMV were only designed for uniform and steady state environments. Tests consisted in applying thermal stress (cooling or heating) on local body surfaces (the body was divided into 19 parts) while the rest of the body is exposed to a neutral, warm or cool thermal environment. On the strength of 109 human subject tests performed in the UC Berkeley climate-controlled chamber and a set of tests carried out in an automobile placed within a climate-controlled wind tunnel at the Delphi Harrison facility in Lockport, NY, Zhang came up with a local thermal sensation and a local thermal comfort model for each body part as well as a model for the overall thermal sensation and the overall thermal comfort.

3.1.1 Zhang overall sensation model

The Zhang global sensation model S_o as proposed in [31] is the weighted average of local sensations on 19 body parts. It stipulates that some body parts have larger weight than others and that weighting for each body part can be different depending whether it is warmer or cooler than the mean

sensation. The importance of local asymmetry is emphasized suggesting a weight factor for each body part as a function of difference between the local and the average sensation. The global sensation is measured on a 9-point ASHRAE-scale ranging from -4 (very cold) to 4 (very hot).

$$S_o = \frac{\sum_{i=1}^{19} w_i S_i}{\sum_{i=1}^{19} w_i} \quad (1)$$

where S_i is the local sensation on the body part i obtained from people votes and w_i is the weighting factor,

$$w_i = a_i(S_i - S_m) \quad (2)$$

with a_i parameters of the individual body parts (numerical values are given in Table 6.4 in [31]) and S_m the area weighted average sensation,

$$S_m = \frac{\sum_{i=1}^{19} A_i S_i}{\sum_{i=1}^{19} A_i} \quad (3)$$

In [34], Zhang proposed to reconsider the way of evaluating the overall sensation. Two different conditions are addressed separately:

- there are body parts feeling a strong opposite sensation ($Sl < 0$ for instance) compared to the sensation felt by the others ($Sl \geq 0$) which represent the majority of the body parts;
- There are no body parts feeling an opposite sensation regarding the other body parts ($Sl \geq 0$ or $Sl \leq 0$ for all body parts).

In the first case, body parts feeling opposite sensations act to pull the overall sensation of the rest of the body parts towards them. Each body part feeling opposite sensation can be viewed as creating an individual force in order to modify the overall sensation of the rest of the body. In the second case, the overall sensation is driven by the most extreme sensations ($|Sl| \geq 2$) creating a sort of complaint in the mind. When there are no extreme local sensations, the complaint-driven process becomes less obvious and the overall sensation approaches the average of all the local sensations.

The overall sensation model is compared to the people votes collected during the experimental campaign. For different test scenarios in hot and cool thermal stress (A, B and C presented in the previous section), people

local sensation votes are recorded and given as inputs to the Zhang overall sensation model. The output is averaged regarding to the number of human subjects and compared to the averaged actual people votes. In Fig.9, the average people vote is depicted with a plain line and the standard deviation by a solid stripping around the mean vote. Both Zhang models (the original one dating from 2003 and the revised one dating from 2010) are also represented. A good match between the experimental data and the models is found. The revised version is performing better than the original one as for the most of the time the model is close to the mean vote and almost always under the standard deviation.

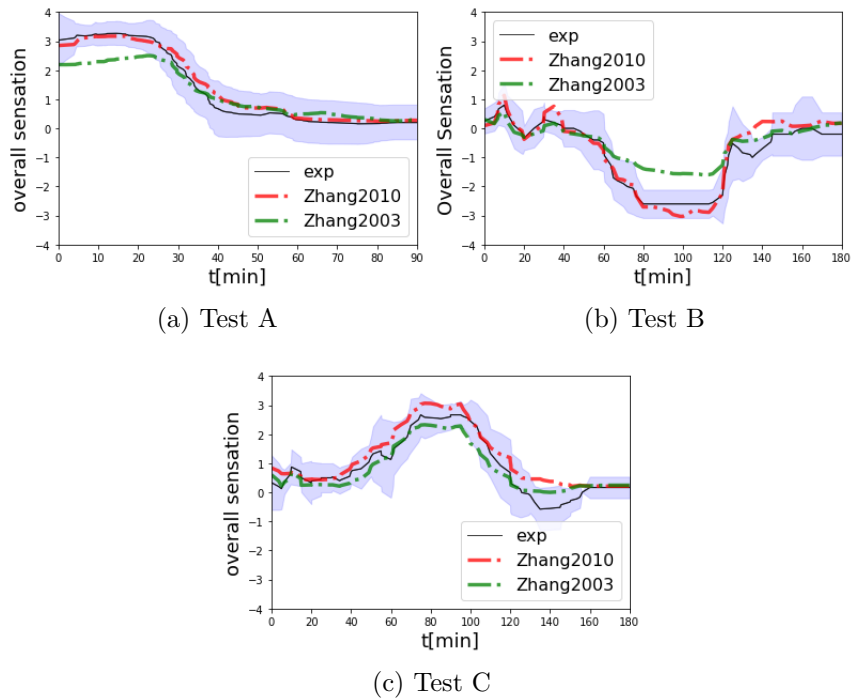


Figure 9: Comparison of the Zhang overall sensation model with people votes

3.1.2 Zhang local comfort model

The formula for the local thermal comfort index derived by Zhang[31] is based on effects seen in the literature and in the experimental data collected during her own tests. It is observed that the hotter or colder people are, the

more uncomfortable they feel[35]. Moreover, based on the overall sensation the local sensation at which the maximum comfort occurs is shifted to the cooler or the warmer side. For instance, when the whole body is warm, local cold or cool stimuli are perceived as pleasant[36, 37]. It is also observed that when thermal stimuli remove the heat stress or relieve the discomfort, sensation of pleasure is created and the magnitude of the comfort is increased. Compared to the magnitude of maximum comfort in neutral overall thermal state, its value is shifted and increased asymmetrically when the overall thermal state is warm or cold[38, 39, 40, 41]. The comfort is measured on a 9-point ASHRAE-scale ranging from -4 (very uncomfortable) to 4 (very comfortable).

$$Lc = \left[\frac{le_slope - ri_slope}{\exp(5(Sl + offset)) + 1} + ri_slope \right] \cdot f + Lc_{max} \quad (4)$$

with

$$So < 0 = \begin{cases} offset = C_8 + C_{31} \cdot |So| \\ Lc_{max} = C_6 + C_{71} \cdot |So| \end{cases} \quad (5)$$

$$So \geq 0 = \begin{cases} offset = C_8 + C_{32} \cdot |So| \\ Lc_{max} = C_6 + C_{72} \cdot |So| \end{cases} \quad (6)$$

and

$$le_slope = \frac{4 + Lc_{max}}{|-4 + offset|^N}, \quad ri_slope = \frac{-4 - Lc_{max}}{|4 + offset|^N} \quad (7)$$

and

$$\begin{aligned} Sl + offset < 0 &\rightarrow f = -|Sl + offset|^N \\ Sl + offset \geq 0 &\rightarrow f = |Sl + offset|^N \end{aligned} \quad (8)$$

In the revised version, the framework of the model and the assumptions are kept identical to the original model but a number of the model coefficients have been modified (see [33]).

It has been noticed that for some body parts the revised model of Zhang [33] is not matching the trend of people votes when the sensation indices are negative (see Fig.10a). It is then recommended to use the original version of the Zhang [31] model for local comfort predictions.

As presented in Fig.10, local comfort can differ from one body part to another even if they are experiencing the same quasi-homogeneous cool thermal stress. Local comfort on hands (see Fig.10c) is not very sensitive to thermal strain (at $t = 60$ min) or relief (at $t = 120$ min). Belly (see Fig.10d), thighs, upper arms and back are body parts resisting to comfort deterioration as the comfort level decreases slowly. However, they react promptly to a thermal solicitation that pull them from a discomfort zone (as it can be seen at $t = 120$ min Fig.10d when the temperature setpoint is switched to $25C$). Lower legs (see Fig.10a), neck, head and face are moderately sensitive to comfort deterioration or recovery. And conversely, feet (see Fig.10b) and forearms are very sensitive body parts. When experiencing quasi-homogeneous warm thermal stress(see Fig.11), sensitivity of body parts differs from the trend that has been observed during cool thermal solicitations. Effectively, only head and face evidence a high deterioration of the local comfort (see Figs.11b and 11d) whereas the deterioration remains moderate on the other body parts (see Figs.11a and 11c).

Regarding test A, for body parts such as chest, head (see Fig.11b) or feet the model is close to the mean vote. As for the rest of the body parts (lower arms, belly, lower legs, upper arms, upper back, lower back, thighs, neck and hands (see Fig.11a)), there is a good qualitative accordance between the model and the vote although the quantitative differences between the model and the mean vote can be higher and reach 2 points on a 9-point ASHRAE-scale. The worst case is presented in Fig.11a. One can notice that the original Zhang model predicts on the left hand a comfort which is 2.5 points lower than the mean vote at $t = 0$ min. Despite the fact that the model prediction is quite far from the mean vote, it still remains close to the range $\pm\sigma$ where σ is the root mean square deviation. It is also worth noting that the standard deviation can be quite large and the $\pm\sigma$ interval range can cover 3 to 4 points on a 9-point ASHRAE-scale. This high deviations are mainly due to the variability of the thermal environment people experienced during the test (see Fig.7) and the effect of testers inter-variability in terms of psychology, physiology and physical morphology on the sensation and comfort perceptions.

Likewise, people local comfort votes during the test scenario B are compared to Zhang models. Despite the high discrepancies observed on body parts such as hands (see Fig.10c), upper arms, back, belly (see Fig.10d), neck, chest, head or thighs, fair agreements are found between the people votes and the Zhang model on the other body parts (forearms, lower legs

(Fig.10a),feet (Fig.10b)).

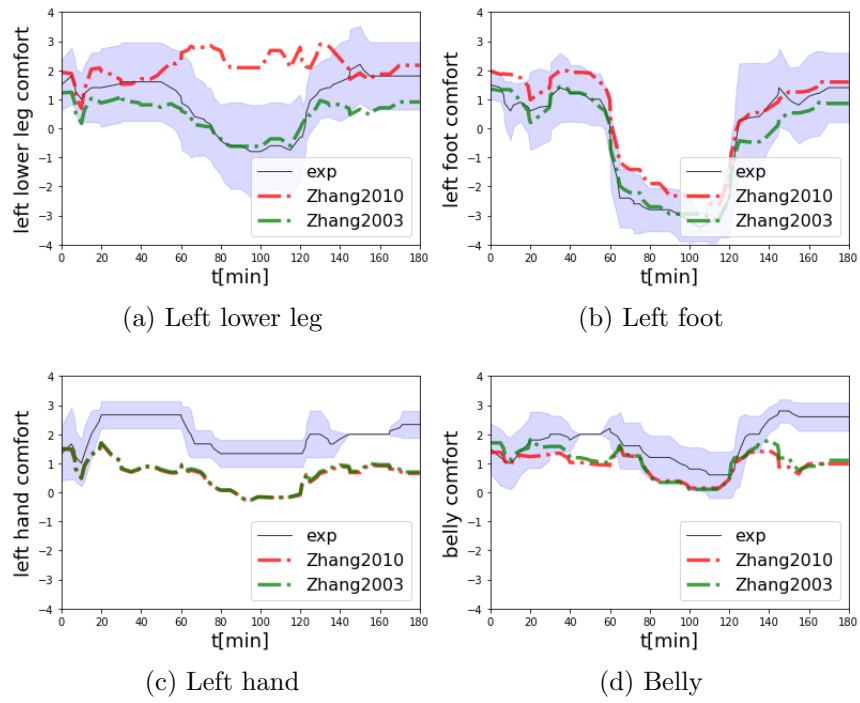


Figure 10: Examples of local comfort on body parts when experiencing cool thermal stress

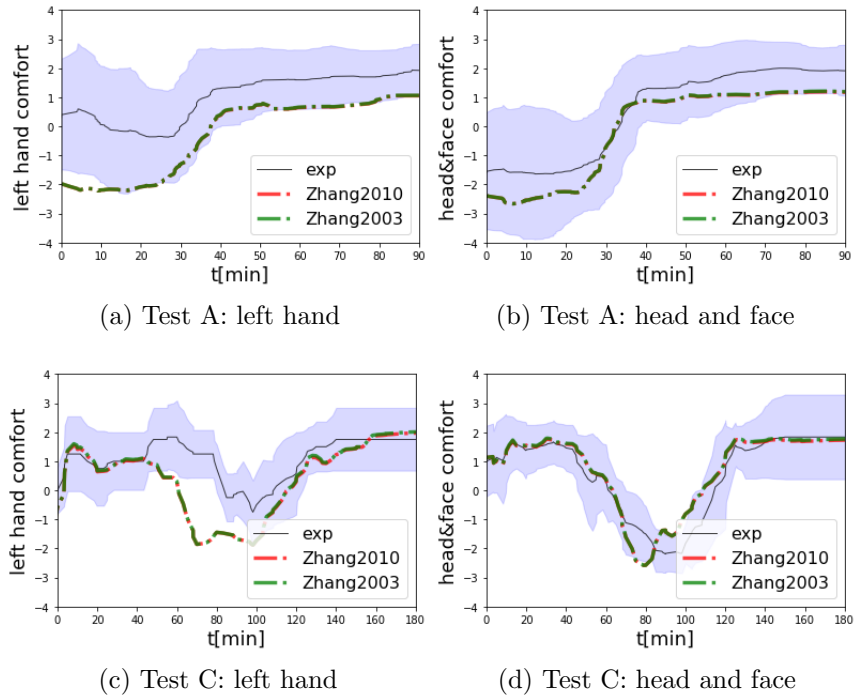
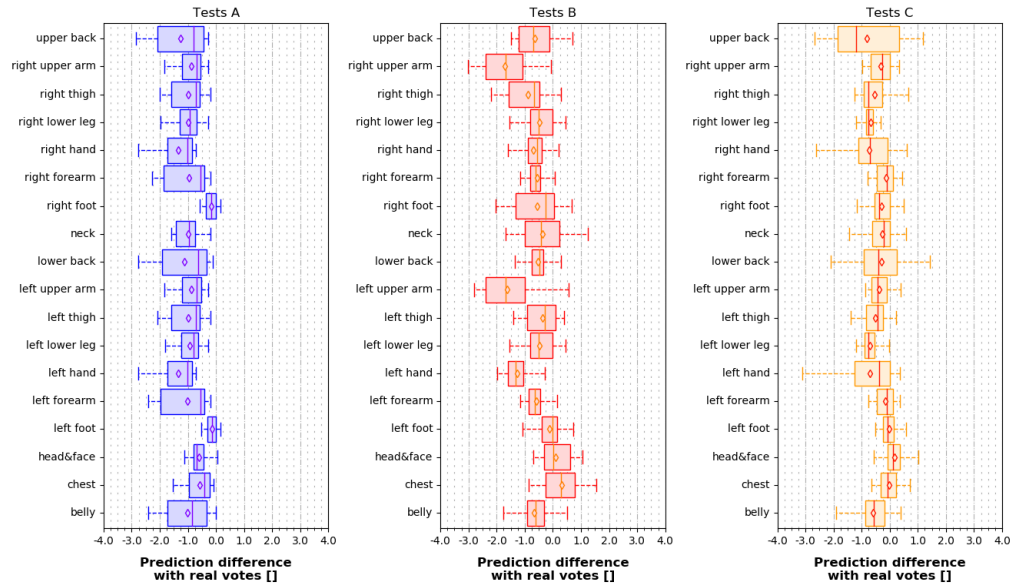
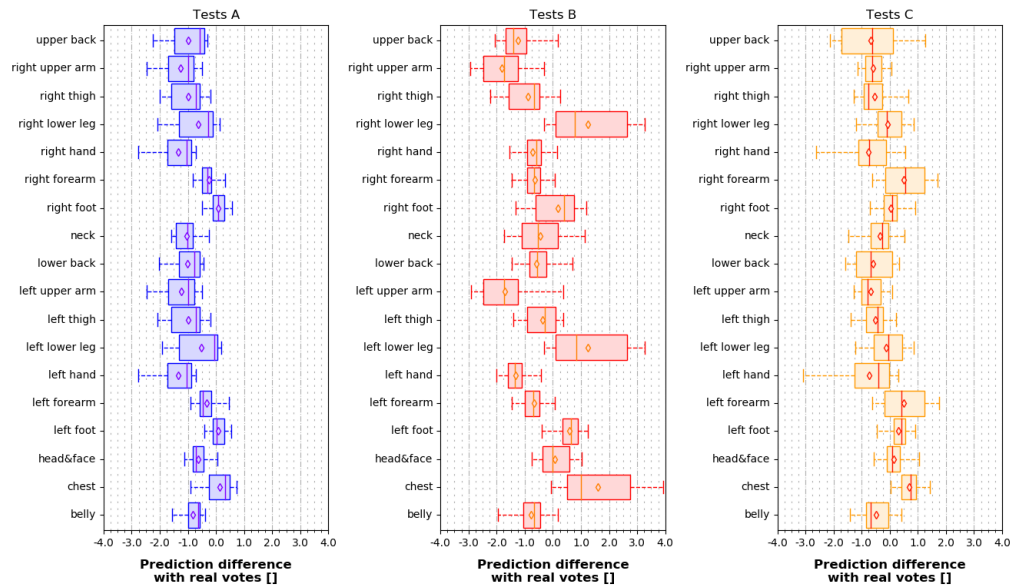


Figure 11: Examples of local comfort on body parts when experiencing warm thermal stress

As for the test scenario C, if for body parts such as head and face (see Fig.11d) feet, neck, belly, chest, thighs, lower back, lower legs, forearms or upper arms, there is a good matching between the model and the mean people vote, discrepancies are found on other body parts such as hands (see Fig.11c) and upper back.



(a) Discrepancies between the original model of Zhang and the mean vote



(b) Discrepancies between the revised model of Zhang and the mean vote

Figure 12: Box plots illustrating the distribution of discrepancies between models prediction and the mean vote.

Fig.12 summarizes the deviation distribution between predictions computed with the both Zhang models and peoples vote on all the body parts. It can be observed that on the whole, Zhang models are more likely to predict a low level of comfort than the vote of peoples. Moreover, it is observed that the revised version is less accurate than the original one, supporting our recommendation to use the original version of the Zhang model to predict local comfort.

3.1.3 Zhang overall comfort model

Zhang observed that the overall comfort follows a complaint pattern. In other words, the most uncomfortable body parts have crucial impacts on the overall comfort perception.

When the thermal conditions are transient or when the subject is allowed to control his/her thermal environment, the overall comfort is evaluated as the average of the two minimum and the maximum local comfort votes. Otherwise, the overall comfort is the average of the two minimum local comfort votes.

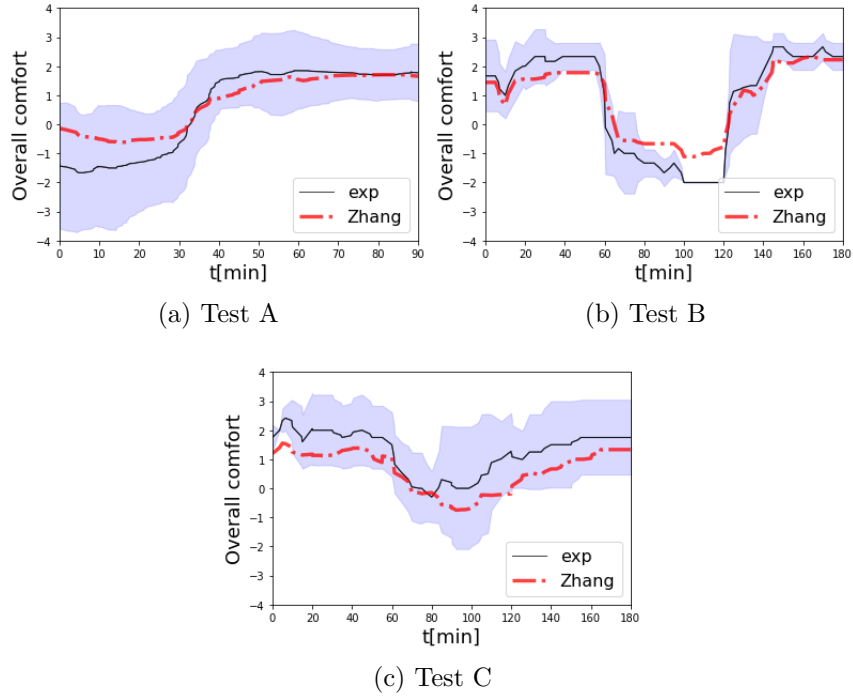


Figure 13: Comparison of the Zhang overall comfort model with people votes

The overall comfort as shown in Fig.13 is very well predicted by the Zhang model for both hot and cool test scenarios.

In conclusion, based on the experimental observations it seems that the revised Zhang model [33] better predicts global sensation and comfort whereas the original one [31] shows greater performances in predicting local comforts. Moreover, it is worthwhile to notice as evidenced with tests B that Zhang local comfort models predict poorly the experimental trend in cool/cold environments.

3.2 Parametric study and suggestions

The Zhang comfort model was compared to people votes in an automobile environment and a good qualitative accordance was found particularly in warm environment supporting hence the following parametric study. The aim of this investigation is to represent graphically noticeable trends of the local comfort regarding to body zones local sensation and the global sensation

with a view to deduce usable strategies for heating and cooling system inside of an automobile cabin (Fig.14). It is noticed that based on the previous comparison of the two models of Zhang[31, 33] with people votes in warm and cold environments, the original version of the Zhang[31] model seems to better represent the local comfort. Therefore, we have decided to take into consideration the coefficients of the original version and do the interpretation accordingly.

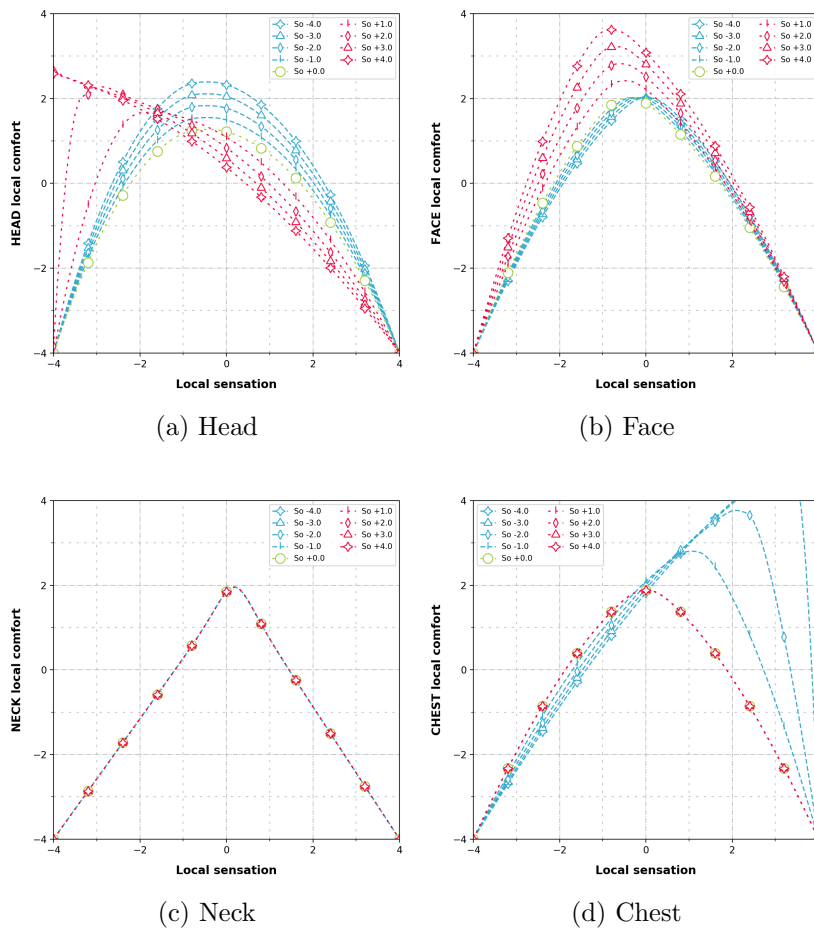
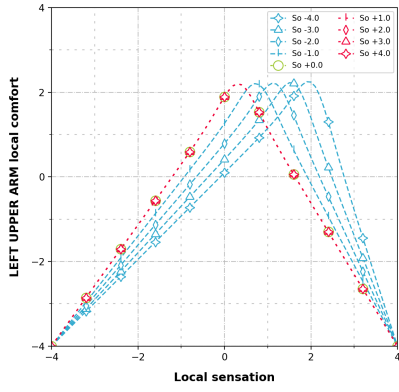
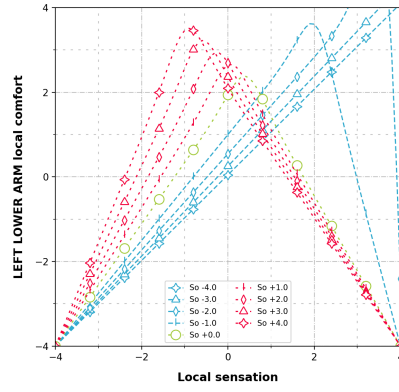


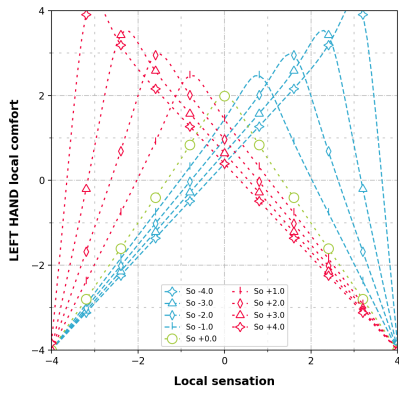
Figure 14: Local thermal comfort for different local and global thermal sensations



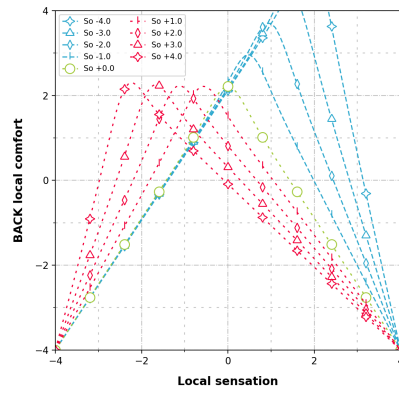
(e) Upper Arms



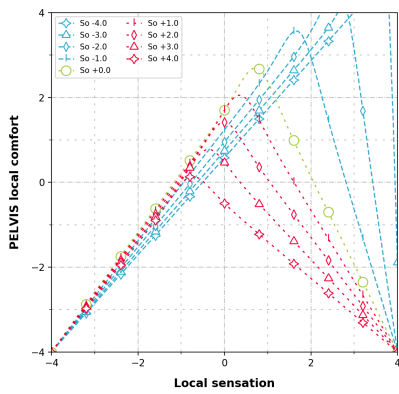
(f) Lower Arms



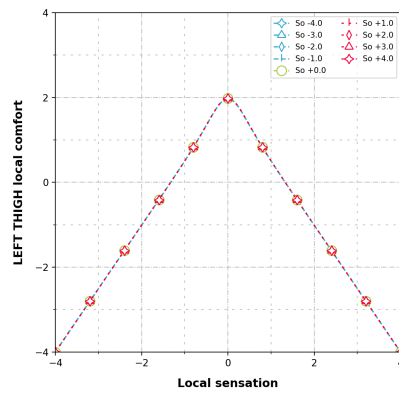
(g) Hands



(h) Back



(i) Pelvis



(j) Thighs

Figure 14: Local thermal comfort for different local and global thermal sensations (cont.)

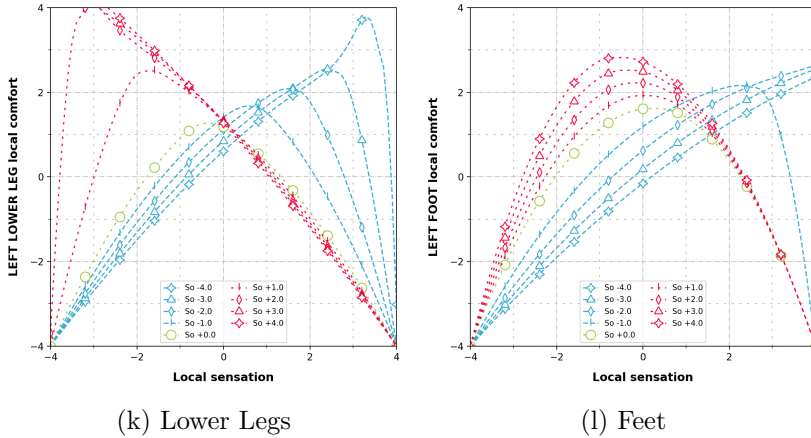


Figure 14: Local thermal comfort for different local and global thermal sensations (cont.)

When a thermal stress is applied on a body part, it is seen that the local comfort felt on that body part depends on the global thermal stress of the entire body. Moreover, its response to the thermal stress in terms of local sensation of pleasure can have a very different trend to the one observed on another sector of the body. Understanding the evolution of the local body parts comfort preferences in various local and global thermal stresses enables to better set the HVAC system instructions.

The equation 4 has been plotted for each body part as a function of local sensation in different thermal ambiances represented by the global sensation parameter. The local comfort perception on the neck and thighs are independent of the overall thermal sensation. The maximum local comfort is centred on the thermal neutrality ($So = 0$ and $Sl = 0$) for the thighs and slightly shifted to the warm side for the neck. The local comfort decreases linearly when local sensation moves away from the thermal neutrality state irrespective of the global sensation (Figure 14c, Figure 14j). Neck and thighs need then to be kept around thermal neutrality.

Maximum local comfort is reached on the face body part when it is slightly refreshed from thermal neutrality and compared to the neck or thighs, the comfort zone (range of the local sensations for which the local comfort is positive, $Cl \geq 0$) is wider suggesting a greater tolerance regarding to the thermal stress. Moreover, the asymmetrical shift of the maximum local comfort when moving from the global thermal neutrality ($So = 0$) shows that

the face body part should be kept in a cool environment. Effectively, when the overall sensation is getting hotter and hotter the face is feeling more and more comfortable when it is kept cool. However, when the global sensation is getting colder and colder the face requires thermal neutrality to feel the maximum comfort (Figure 14b).

The head needs to be cooled in environments leading to warm global sensations, and kept around thermal neutrality in cold environments. It is worthwhile to notice that the comfort zones are wide and the comfort feelings are not symmetrical when moving from the global thermal neutrality ($So = 0$). It should be noticed that local comfort predictions of Zhang in hot environments are unrealistic as the local comfort model fails to drop when the local sensation becomes very cold (Figure 14a).

Hands have a narrow comfort zone at the thermal neutrality state of the body ($So = 0$). It widens when the overall sensation moves away from the neutral thermal sensation. The maximum comfort is also shifted away symmetrically from the thermal neutrality state with the enlarging distance between the overall sensation and the neutral overall thermal sensation. For instance when the overall sensation is cold, heating the hands will raise its local comfort to a great comfort but when the heating exceeds a certain threshold the felt comfort drops very abruptly (Figure 14g).

The comfort zone is wide for the feet suggesting that they can tolerate a wide range of thermal stress. People seem to be more comfortable with warm feet than with cold ones. Therefore, a local solution for enhancing thermal comfort inside a cabin would be to locally heat the feet in cold global conditions whereas the feet in warm global condition must be cooled with caution (feet prefer to be refreshed than cooled). Otherwise, the comfort may drop abruptly (Figure 14l). It should be also noticed that local comfort predictions of the Zhang model are unrealistic in cold environments as the feet local comfort do not drop when the local sensation becomes extreme.

When the overall sensation is cold, warming the pelvis region increases the local comfort but only up to a certain level. For instance, for a cold global sensation of $So = -2$, a warm local sensation of ($Sl = 2.5$) is perceived with a comfort level higher than 4 on the 9-point scale but when the heat applied is too hot ($Sl > 2.5$), the comfort drops sharply. On the other side, cooling the pelvis when the global sensation becomes warmer do not improve the local comfort. It suggests that there is no need for instance to equip an active seat with cooling devices in order to refresh the pelvis area in hot thermal conditions (Figure 14i).

The chest behaviour is similar to the pelvis but has a slightly wider comfort zone. Local warming of the chest does increase significantly thermal comfort when the body is cold. However, local cooling of the chest does not improve the thermal comfort when the body is warm (Figure 14d).

Upper arms seem to be body parts with a secondary importance for an HVAC as whatever the effort put to heat this body part, it would only result on moderate satisfaction level in cold environment. Moreover, no improvement can be expected in cooling this body part in hot environments (Figure 14e).

The back is an excellent candidate to warm in priority in cold environments as great comfort can be reached by slightly warming this zone. It also means that the comfort can degrade if the heating is felt too hot. In hot environments, it must be refreshed cautiously as it seems to tolerate only cool thermal stress (Figure 14h).

In cold environments heating lower arms enables to improve the local comfort even if local comfort predictions are unrealistic in extreme cold conditions. In warm environments, only slight cooling can be applied in order to prevent a comfort degradation on this zone (Figure 14f).

Lower legs behaves similarly to the hands except that there is no symmetry in the shift of the maximum comfort when the global sensation moves away from the neutral sensation (Figure 14k).

From examining the different patterns for each body part, one sees that the thermal local or global sensations are not very meaningful to give instructions in order to optimize comfort whereas the local thermal preferences for each body part are much more relevant. For instance, under global neutral conditions ($So = 0$), the face and lower legs show a preference for a slightly cool local sensation whereas the pelvis and arms show a preference for a warm local sensation. The chest, the back, thighs and hands do not show any preference in neutral conditions. Therefore, to achieve a maximum comfort at neutral conditions heating of the pelvis is recommended while slightly cooling the face. However, it is worthwhile to notice that these directives are linked only to the temperature of the HVAC system as the speed of the air or the humidity, which are also sources of comfort and discomfort, are not considered in the Zhang model. Depending on the objective one is looking for, the HVAC system can be set accordingly. Optimizing comfort requires for each body part a focus on the level of local sensation that corresponds to the maximum of its local comfort. However, optimizing the energy use requires that the HVAC system maintains local sensations level so that local comforts

Table 1: Maximum local thermal comfort and its corresponding local sensation for a cold global thermal sensation $So = -2$

Body Element	Maximum C_{loc}	Corresponding S_{loc}
Head	1.9	-0.5
Face	2	-0.24
Neck	1.9	0.24
Chest	3.7	2
Upper Arms	2.2	1
Lower Arms	4	3.2
Hands	2.97	1.55
Back	3.6	1
Pelvis	4	2.5
Thighs	1.95	0
Lower Legs	2	1.5
Feet	2.6	4

Table 2: Maximum local thermal comfort and its corresponding local sensation for a warm global thermal sensation $So = 2$

Body Element	Maximum Cl	Corresponding Sl
Head	2.25	-2.85
Face	2.82	-0.57
Neck	1.9	0.24
Chest	1.8	0
Upper Arms	2.1	0.24
Lower Arms	3	-0.24
Hands	3	-1.5
Back	2.1	-1.1
Pelvis	1.4	0
Thighs	1.95	0
Lower Legs	4	-3
Feet	2.2	-0.2

remain positive. Let's consider a cold global thermal sensation of $So = -2$. The maximum level of comfort and the local thermal sensation for which this

Table 3: Maximum local thermal comfort and its corresponding local sensation for a very cold global thermal sensation $So = -4$

Body Element	Maximum Cl	Corresponding Sl
Head	2.4	-0.5
Face	2.0	0
Neck	1.94	0.24
Chest	4	2.7
Upper Arms	2.16	1.9
Lower Arms	4	3.9
Hands	4	3
Back	4	1.8
Pelvis	4	3.5
Thighs	1.96	0
Lower Legs	3.8	3.4
Feet	2.3	4

comfort is reached are displayed in Table 1. Thus, we can see that for a cold global sensation chest, feet, lower arms and the pelvis have a preference to be vigorously heated whereas the back, hands, lower legs and upper arms need to be slightly heated (max $Sl = 2$). Head, face, neck and thighs rather prefer a sensation near the thermal neutrality. The HVAC strategy can then be set accordingly with a maximum and minimum thermal power applied respectively on the feet and the face. An energy saving strategy would be to keep the head cold ($Sl = -2$) while maintaining arms, hands, feet and the pelvis around thermal neutrality and other body parts cool ($Sl = -1$). For a warm global thermal sensation of $So = 2$ (Table 2), cooling lower legs and the head vigorously, cooling hands and the back moderately and refreshing slightly the face while maintaining the other body parts such as the neck, chest, thighs, pelvis, arms and feet around the thermal neutrality will be the best possible scenario for optimizing comfort in this situation. An energy saving strategy would be to maintain face, chest and feet hot while keeping the rest of the body parts slightly warm leading to large improvements in local thermal comfort with a moderate thermal effort.

In a very cold environment, ($So = -4$) feet, chest, pelvis, arms, lower legs and hands have to be vigorously heated whereas the back side need to be only moderately heated. Moreover, the head, face, neck and thighs

Table 4: Maximum local thermal comfort and its corresponding local sensation for a very hot global thermal sensation $So = 4$

Body Element	Maximum C_{loc}	Corresponding S_{loc}
Head	2.6	-4
Face	3.62	-0.73
Neck	1.94	0.24
Chest	1.9	0
Upper Arms	2.1	0.3
Lower Arms	3.5	-0.95
Hands	4	-3
Back	2.2	-2.2
Pelvis	0.1	-0.7
Thighs	1.96	0
Lower Legs	4	-4
Feet	2.9	-0.5

have to be maintained around thermal neutrality. An energy saving strategy would be heating moderately the feet and leaving relatively cold the head ($Sl = -2$) while keeping arms, hands, pelvis and lower legs around the thermal neutrality and the other body parts relatively cool ($Sl = -1$). In a very hot environment ($So = 4$), the head, hands, lower legs and the back have to be vigorously cooled whereas the other body parts need to be maintained around thermal neutrality. An energy saving strategy would be to keep refreshed the pelvis while head, hands and the back are maintained around thermal neutrality. Feet, chest and the face have a large resiliency zone so that they can be kept warm ($Sl = 2$) whereas other body parts can be maintained slightly warm ($Sl = 1$).

From the above analysis, it is showed that smart and local thermal solicitations on specific body parts can be set to prevent from comfort deterioration when the whole body is placed in a discomfort zone. Such an investigation would not be possible to consider using the PMV-PPD model as it has been derived to compute the physiological response of the body in terms of sensation (heat balance between the body and environment) and thus ignores the influence of the psychological effect in the prediction of people comfort (concept of pleasure when leaving the discomfort zone for instance).

4 Conclusion

In this study, it is proposed to confront Zhang models prediction to people votes in car cabin situations in transient and quasi-homogeneous cool and warm environments. The original Zhang model is suggested for estimating the local comfort. It is observed that for the most of the body parts, quite good qualitative agreements are found between predictions and actual votes in warm and cool environments. However, the Zhang local comfort model has to be improved for a number of body parts. The revised Zhang model is recommended for the global sensation prediction from local sensations and for the model giving the global comfort from local comforts. The global sensation and comfort models showed very satisfying performances regarding the experimentally obtained votes. As can be noticed, the present study targeted mainly transients scenarios and the next steps would be to confront experimentally the Zhang model in very asymmetric environments (sun load on the upper body parts for instance).

Based on this initial results, a parametric study has been carried out. Thermal preferences seem to be impacted by the thermal state of the entire body and are very different from one body part to another. For different thermal ambiances experienced by the human body and measured by means of the overall sensation, body parts that need to be handled in priority are identified enabling to set adequate strategies to bring them back to comfort. Comfort-oriented and energy saving-oriented (downgraded mode) strategies are suggested and it is noticed that depending on the strategy, body parts that need to be focused and the resulting HVAC settings can be very different.

The PMV-PPD approach is not the appropriate model to investigate customized solutions with localized strategies on body parts mainly in transient phases (very common in automotive environments) as the concept of pleasure or comfort is not included in this model. The Zhang model appears to be a good candidate for this kind of approaches. Thanks to refined comfort models such as Zhang models, frugal and effective solutions can be conceived to bring comfort to occupants inside car cabins in order to reduce the impact of auxiliaries on EVs range.

References

- [1] J. Hildermeier and A. Villareal. Shaping an emerging market for electric cars: How politics in france and germany transform the european automotive industry. *ERIEP*, 3, 2011.
- [2] K. Kambly and Thomas H. Bradley. Geographical and temporal differences in electric vehicle range due to cabin conditioning energy consumption. *Journal of Power Sources*, 275:468–475, 2015.
- [3] H. Oi, K. Tabata, Y. Naka, A. Takeda, and Y. Tochihara. Effects of heated seats in vehicles on thermal comfort during the initial warm-up period. *Appl. Ergon.*, 2:360–367, 2012.
- [4] H. Oi, K. Yanagi, K. Tabata, and Y. Tochihara. Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle. *Ergonomics*, 8:690–699, 2011.
- [5] Y. F. Zhang, D. P. Wyon, L. Fang, and A. K. Melikov. The influence of heated or cooled seats on the acceptable ambient temperature range. *Ergonomics*, 4:586–600, 2007.
- [6] J. E. Brooks and K. C. Parsons. An ergonomics investigation into human thermal comfort using an automobile seat heated with encapsulated carbonized fabric (ecf). *Ergonomics*, 42:661–673, 1999.
- [7] W. Pasut, H. Zhang, E. Arens, and Y. Zhai. Energy-efficient comfort with a heated/cooled chair: Results from human subjects tests. *Build. Environ.*, 84:10–21, 2015.
- [8] M. Vesely and W. Zeiler. Personalized conditioning and its impact on thermal comfort and energy performance - a review. *Renew. Sustain. Energy Rev.*, 34:401–408, 2014.
- [9] ISO. *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles Part 1: Principles and methods for assessment of thermal stress*. ISO 14505-1:2007, 2007.
- [10] ISO. *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles Part 2: Determination of equivalent temperature*. ISO 14505-2:2006, 2006.

- [11] ISO. *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles Part 3: Evaluation of thermal comfort using human subjects*. ISO 14505-3:2006, 2006.
- [12] ASHRAE. *Thermal environmental conditions for human occupancy, ANSI/ASHRAE Standard 55-2013*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2013.
- [13] H. O. Nilsson. *Comfort climate evaluation with thermal manikin methods and computer simulation models*. PhD thesis, PhD Thesis, University of Gavle, 2004.
- [14] H. O. Nilsson. Thermal comfort evaluation with virtual manikin methods. *Build. Environ.*, 42:4000–4005, 2007.
- [15] T. Han and L. Huang. A sensitivity study of occupant thermal comfort in a cabin using virtual thermal comfort engineering. *SAE Paper Series*, 2005-01-0633, 2015.
- [16] O. Fanger. *Thermal comfort-analysis and applications in environmental engineering*. C.D.T. Press, 1970.
- [17] A. Alahmer, M. Abdelhamid, and M. Omar. Design for thermal sensation and comfort states in vehicles cabins. *Appl. Therm. Eng.*, 36:126–140, 2012.
- [18] D. Ruzic and F. Casnji. Thermal interaction between a human body and a vehicle cabin. *Heat. Transf. Phenom. Appl.*, pages 295–318, 2012.
- [19] M. Simon, L. Socaciu, and P. Unguresan. Factors which influence the thermal comfort inside of vehicles. *Energy Proc.*, 85:472–480, 2015.
- [20] M. Cisternino. *Thermal climate in cabs and measurement problems*. Paper for the CABCLI seminare EC Cost Contract No SMT4-CT98-6537 (DG12 BRPR), Dissemination of results from EQUIV e EC Cost Contract No SMT4-CT95-2017, 1999.
- [21] X. Zhou, D. Lai, and Q. Chen. Experimental investigation of thermal comfort in a passenger car under driving conditions. *Build. Environ.*, 149:109–119, 2019.

- [22] Y. Wang and Z. Lian. A thermal comfort model for the non-uniform environments. *Energy and Buildings*, 172:397–404, 2018.
- [23] B. Koelblen, A. Psikuta, A. Bogdan, S. Annaheim, and R. M. Rossi. Thermalsensation models: Validation and sensitivity towards thermophysiological parameters. *Build. Environ.*, 130:200–211, 2018.
- [24] D. Fiala. *Dynamic Simulation of Human Heat and Thermal Comfort*. PhD thesis, De Montfort University, 1998.
- [25] J. Joris, S. Mokdad and R. El Khoury, and G. Crehan. *Experimental validation of a multi-solver heat transfer simulation methodology including occupant thermo-physiology*. PhD thesis, 12th International Manikin and Modelling Meeting, St. Gallen, Switzerland, 29-31 August 2018.
- [26] I. Thiagalingam, S. Mokdad and R. El Khoury, and T. Tanguy. *Confrontation of thermal sensation and comfort models to votes in a transient thermal exposure*. PhD thesis, 12th International Manikin and Modelling Meeting, St. Gallen, Switzerland, 29-31 August 2018.
- [27] K. Katic, R. Li, and W. Zeiler. Thermophysiological models and their applications: a review. *Build. Environ.*, 106:286–300, 2016.
- [28] D. Enescu. A review of thermal comfort models and indicators for indoor environments. *Renew Sustain Energy Rev.*, 79:1353–1379, 2017.
- [29] M. Fu, W. Weng, W. Chen, and N. Luo. Review on modeling heat transfer and thermoregulatory responses in human body. *Therm. Biol.*, 62:189–200, 2016.
- [30] Y. Cheng, J. Niu, and N. Gao. Thermal comfort models: A review and numerical investigation. *Build. Environ.*, 47:13–22, 2012.
- [31] H. Zhang. *Human thermal sensation and comfort in transient and non-uniform thermal environments*. PhD thesis, University of California, 2003.
- [32] H. Zhang, E. Arens, and C. Huizenga. *Thermal sensation and comfort models for non-uniform and transient environments: Part I: local sensation of individual body parts*. PhD thesis, UC Berkeley: Center for the Built Environment, 2009.

- [33] H. Zhang, E. Arens, and C. Huizenga. *Thermal sensation and comfort models for non-uniform and transient environments: Part II: local comfort of individual body parts*. PhD thesis, UC Berkeley: Center for the Built Environment, 2009.
- [34] H. Zhang, E. Arens, and C. Huizenga. *Thermal sensation and comfort models for non-uniform and transient environments: Part III: whole-body sensation and comfort*. PhD thesis, UC Berkeley: Center for the Built Environment, 2009.
- [35] D. Wang, H. Zhang, E. Arens, and C. Huizenga. Observation of upper-extremity skin temperature and corresponding thermal sensations. *Building and Environment*, 42:3933–3943, 2007.
- [36] H. Hensel. *Thermal sensation and thermoreceptors in man*. Springfield, Charles C Thomas, 1982.
- [37] M. Cabanac. Plaisir ou deplaisir dela sensation thermique et homeothermie. *Physiology and Behavior*, 4:359–364, 1969.
- [38] DM. Mower. Perceived intensity of peripheral thermal stimuli is independant of internal body temperature. *Journal of Comparative and Physiological Psychology*, 90:1152–1155, 1976.
- [39] M. Attia. Thermal pleasantness and temperature regulation in maan. *Neuroscience and Biobehavioral Reviews*, 8:335–342, 1984.
- [40] S. Kuno. *Comfort and pleasantness*. PhD thesis, PAN PACific Symposium on Building and Urban Environmental Conditions in Asia, Nagoya, Japan, 1995.
- [41] M. Cabanac. Pleasure: the common currency. *Journal of Theoretical Biology*, 155:173–200, 1992.