Prediction of Automotive Seating Thermal Discomfort related to Wetness Perception

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Abstract Sweat production during summertime inside vehicle cabins may lead to an accumulation of heat and moisture at the seat-person interface increasing microclimate vapor pressure (p_{mic}) and skin wettedness and consecutively causing local thermal discomfort. Currently applied comfort models focus on the convective and radiative heat transfer disregarding evaporation associated with wetness perception (*WP*). Therefore, this laboratory study aimed at providing a model predicting *WP* by p_{mic} serving as comfort benchmark. One-hundred-and-twelve young adults (56 females, 56 males) wearing summer clothing with estimated insulation of 0.6 clo participated in 2h-sessions under heat stress in a climatic chamber occupying a car seat fastened by a 4-point seat belt to reduce body movements to a minimum. We calculated p_{mic} from the continuously recorded temperature and relative humidity of the seat-clothing microclimate at the cushion and the backrest, respectively. We registered *WP* every 5 min in the first hour and every 10 min in the second hour of exposure applying a 5-point scale, which we dichotomized for classifying a vote as a definite *WP*. Applying logistic regression analysis to these training data, we developed models predicting *WP* by p_{mic} and by additional predictors. Percentage of persons stating *WP* significantly increased with p_{mic} and the root-mean-squared prediction error (*rmse*) was 5.2%. With exposure time as additional predictor, *rmse* decreased to 2.5%. We compared the model predictions to independent test data obtained in similar studies with different types of automobile seats under varied thermal conditions. The model with p_{mic} and time as predictors yielded unbiased *WP* estimates with *rmse* below 10% for climatic conditions similar to the training conditions. For neutral or hotter climates, models disregarding the predictor time or substituting it by local or whole body thermal sensations showed improved performance. The apparent effect of exposure time mediated via thermal sensation agrees with the concept of alliesthesia, indicating that alterations in the general thermal state over time may influence *WP* under heat stress. Neutral conditions or auxiliary cooling, e.g. by seat ventilation, might change the temporal relationship so that simpler models based on microclimate vapor pressure alone or in combination with thermal sensation predictions, e.g. by ISO 14505, become preferable. Overall, the introduced models, when used in connection with sensors, thermal manikin measurements or software simulations providing information on microclimate vapor pressure (p_{mic}), show the potential for delivering unbiased estimates of *WP* related discomfort on automobile seats with acceptable error.

Keywords: Thermal comfort, vehicle seat, heat stress, sweating, model.

1 Introduction

The thermal environment represents one of several aspects related to automobile seating comfort [1, 2, 3]. Sweat production during summertime inside vehicle cabins may lead to an accumulation of heat and moisture at the seat-person interface [4] increasing microclimate vapour pressure (p_{mic}) [5] and skin wettedness (w_{sk}) [6] and consecutively causing local thermal discomfort [7, 8]. Although thermal manikins and models [5] are increasingly used for evaluating seating thermal comfort, the underlying comfort models, e.g. ISO 14505, focus on the convective and radiative, i.e. 'dry' heat transfer [9, 10] disregarding evaporation associated with wetness perception (*WP*) [11].

1.1 Objectives

In a study with moderate sample size (n=43), we had recently shown that p_{mic} has equal capacity in predicting *WP* compared to w_{sk} [12]. Therefore, this study aimed at providing a model predicting *WP* by p_{mic} serving as comfort benchmark in manikin and model simulations based on a larger sample, and at validating the resulting model against independent test data obtained with different types of automotive seats under varied climatic conditions.

2 Methods

2.1 Training data

For model development, we obtained training data (*TRAIN*) from one-hundred-and-twelve young adults (56 females, 56 males) wearing short-sleeved T-shirts and jeans with estimated clothing insulation of 0.6 clo, who participated in the climatic chamber experiments. For 2 hours, they were exposed to air temperature $t_a = 25$ °C, mean radiant temperature $t_r = 60$ °C, ambient vapour pressure $p_a = 1.58$ kPa and air velocity $v_a = 0.5$ m/s occupying a car seat fastened by a 4-point seat belt to reduce body movements to a minimum.

2.2 Procedure and measurements

We calculated p_{mic} from the continuously recorded temperature and relative humidity of the seat-clothing microclimate at the cushion and the backrest, respectively, using a Pt100 sensor combined with a capacitance hygrometer (Vaisala HMP 233). We registered *WP* every 5 min in the first hour and every 10 min in the second hour of exposure applying a 5-point scale (1='dry', 2='slightly moist', 3='moist', 4='wet', 5='very wet'), which we dichotomized applying a cut-off scale value greater than two for classifying a vote as a definite *WP*. Concomitantly to *WP*, we also registered thermal sensation votes for the whole body (*TSV*), as well as for body regions located at the seat-person interface (TSV_{loc}), for which we also registered local skin temperatures (Tsk_{loc}) using thermistors (YSI 427).

2.3 Data analysis and model validation

Applying logistic regression analysis with a generalised estimation equation approach to account for the within-subject correlation of the time-dependent observations [13], we developed models predicting the probability of *WP* by p_{mic} as single predictor and by exposure *time*, *TSV*, TSV_{loc} and Tsk_{loc}, respectively, as additional predictors.

For validation purposes, we compared the model predictions to independent test data obtained in similar studies with different types of automobile seats. One study with conventional seats (*CONV*) comprised 2-h-exposures to a thermo-neutral climate with $t_a = t_r = 25$ °C, $v_a = 0.3$ m/s, (*NEUTRAL*, $n = 108$ experiments), and two heat stress conditions with $t_a = 32$ °C (*HEAT1*) and 37 °C (*HEAT2*), respectively, with $t_r = 50$ °C, $v_a = 0.5$ m/s, $n = 107$ for each condition [14]. Another study investigated the effects of 90-min heat exposures similar to *TRAIN* (with t_r reduced to 40-50 °C) on ventilated seats (*VENT*) with $n = 144$ experiments [15].

Prediction errors were calculated as differences of predicted minus observed percentage probability of *WP* for all models applied to the different datasets and were summarized as averaged prediction error (*bias*) and root-mean-squared error (*rmse*), respectively.

3 Results

For *TRAIN*, percentage of persons stating *WP* significantly increased with p_{mic} and the root-mean-squared prediction error (*rmse*) was 5.2%. As *WP* also increased significantly with exposure time, *rmse* decreased to 2.5% after including time as additional predictor (Table 1). Figure 1 depicts the resulting models for the seat backrest and cushion, respectively. Substituting time by thermal sensation or skin temperature as predictors yielded similar *rmse* between 3.6% and 4.5% (Table 1).

For the validation experiments *CONV*, the model with p_{mic} as sole predictor yielded unbiased *WP* estimates with *rmse* = 10.0%, however, adding time as additional predictor caused overestimation with 3% *bias* and increased *rmse* to 14.7% (Table 1). The latter was due to a 19% overestimation bias in the *NEUTRAL* climate accompanied with 11% underestimation in *HEAT2*, whereas for the p_{mic} only model, this *bias* reduced to 7% and -8%, respectively. Predictive accuracy further improved in models replacing exposure time by either global or local thermal sensation, yielding overall *rmse* of 7.6% and 6.8%, respectively (Table 1). Notably, there was negligible *bias* with small *rmse* for *HEAT1*, the condition closest to *TRAIN* (Table 2).

The model with p_{mic} combined with *time* shown in Figure 1 performed best for the validation experiments *VENT* (Table 1), which had been conducted under thermal conditions similar to *TRAIN*.

Under all conditions in Tables 1 and 2, the usage of local skin temperatures did not improve the predictive accuracy compared to models applying time or thermal sensation as additional predictors.

Table 1. Averaged *WP* prediction error (*bias*) and root-mean squared error (*rmse*) from different models for the training data (*TRAIN*) and for independent test data from experiments with conventional (*CONV*) and ventilated seats (*VENT*), respectively.

	TRAIN		*CONV*		*VENT*	
model	*bias*	*rmse*	*bias*	*rmse*	*bias*	*rmse*
p_{mic}	2.4%	5.2%	-0.3%	10.0%	-5.8%	10.0%
p_{mic} + *time*	1.5%	2.5%	3.0%	14.7%	-1.8%	7.3%
p_{mic} + *TSV*	0.6%	4.0%	-1.5%	7.6%	-6.6%	10.5%
p_{mic} + TSV_{loc}	0.0%	3.6%	1.9%	6.8%	-6.5%	10.4%
p_{mic} + Tsk_{loc}	2.2%	4.5%	2.8%	9.6%	-4.6%	9.3%

Table 2. Averaged *WP* prediction error (*bias*) and root-mean squared error (*rmse*) from different models for the different climatic conditions of the independent validation experiments with conventional seats.

	NEUTRAL		*HEAT1*		*HEAT2*	
model	*bias*	*rmse*	*bias*	*rmse*	*bias*	*rmse*
p_{mic}	6.9%	8.7%	0.5%	9.6%	-8.2%	11.5%
p_{mic} + *time*	18.6%	22.0%	1.0%	5.3%	-10.5%	11.5%
p_{mic} + *TSV*	1.6%	2.2%	0.7%	8.7%	-6.7%	9.7%
p_{mic} + TSV_{loc}	1.7%	2.3%	5.8%	9.1%	-1.8%	7.1%
p_{mic} + Tsk_{loc}	8.7%	10.5%	3.9%	8.5%	-4.2%	9.7%

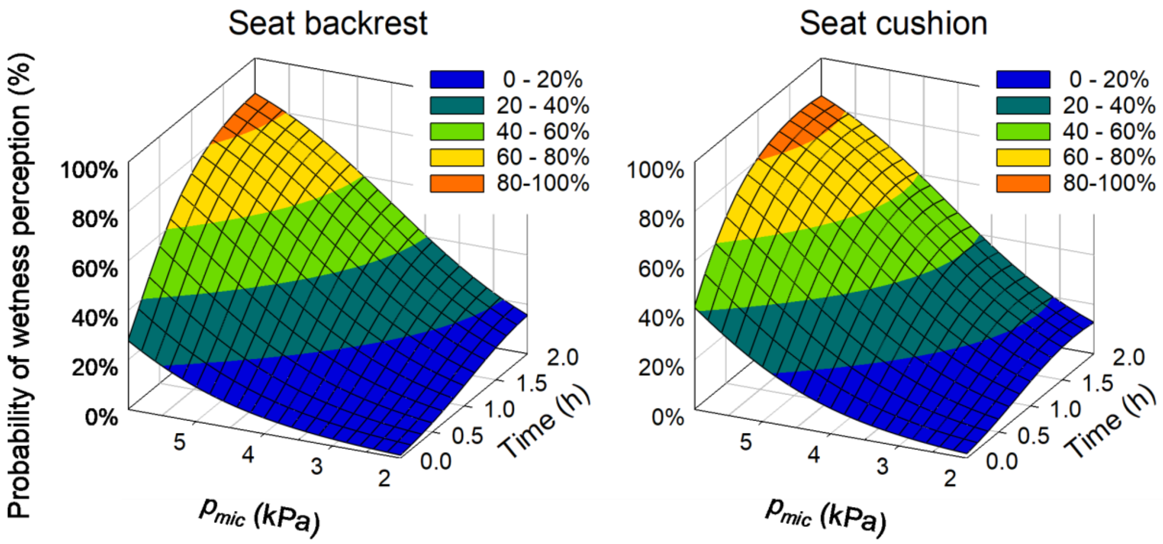

Fig. 1. Models predicting *WP* at the backrest (left) and cushion (right) by p_{mic} and exposure time.

4 Discussion

Though the prediction error was, as expected, higher for the validation data compared to *TRAIN*, our results indicate that the introduced models can deliver unbiased predictions of *WP* related discomfort on car seats with a typical error below 10%.

The apparent effect of exposure time mediated via thermal sensation is in agreement with the concept of alliesthesia [16, 17], indicating that alterations in the general thermal state over time may influence *WP* under heat stress.

Thermal environments closer to neutral conditions or auxiliary cooling, e.g. by seat ventilation, might change the temporal relationship. Thus, simpler models based on microclimate vapour pressure alone or in combination with predicted thermal sensation become preferable, e.g using. ISO 14505-2 [9] or other appropriate algorithms [18, 10]. Local skin temperatures, requiring higher effort in measurement, did not provide any advantage with respect to predictive accuracy in our study.

5 Conclusion

In summary, the introduced models predict the thermal discomfort related to wetness perception on automobile seats and were validated against a large number of controlled experiments under varying climatic conditions with different types of seats. Overall, these models, when used in connection with the information on microclimate vapor pressure (p_{mic}) provided by sensors integrated in the seat, thermal manikin measurements or software simulations, show the potential for delivering unbiased estimates of *WP* related discomfort on automobile seats with acceptable error.

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References

1. Hiemstra-van Mastrigt, S., Groenesteijn, L., Vink, P., Kuijt-Evers, L.F.M., 2017. Predicting passenger seat comfort and discomfort on the basis of human, context and seat characteristics: a literature review. Ergonomics 60, 889-911, doi:10.1080/00140139.2016.1233356.
2. Kolich, M., 2003. Automobile seat comfort: occupant preferences vs. anthropometric accommodation. Applied Ergonomics 34, 177-184, doi:10.1016/S0003-6870(02)00142-4.
3. Vink, P., Hallbeck, S., 2012. Editorial: Comfort and discomfort studies demonstrate the need for a new model. Applied Ergonomics 43, 271-276, doi:10.1016/j.apergo.2011.06.001.
4. Umbach, K., 2000. Climatic comfort of car seats. Tech Usage Text 35, 34-38.
5. Bartels, V.T., 2003. Thermal comfort of aeroplane seats: influence of different seat materials and the use of laboratory test methods. Applied Ergonomics 34, 393-399, doi:10.1016/S0003-6870(03)00058-9.
6. Gagge, A.P., Gonzalez, R.R., 1974. Physiological and physical factors associated with warm discomfort in sedentary man. Environmental Research 7, 230-242, doi:10.1016/0013-9351(74)90154-6.
7. Diebschlag, W., Heidinger, F., Kurz, B., Heiberger, R., 1988. Recommendation for Ergonomic and Climatic Physiological Vehicle Seat Design. SAE Technical Paper 880055, doi:10.4271/880055.
8. Fukazawa, T., Havenith, G., 2009. Differences in comfort perception in relation to local and whole body skin wettedness. European Journal of Applied Physiology 106, 15-24, doi:10.1007/s00421-009-0983-z.
9. ISO 14505-2, 2006. Ergonomics of the thermal environment -- Evaluation of thermal environments in vehicles -- Part 2: Determination of equivalent temperature. International Organisation for Standardisation, Geneva.
10. Zhang, H., Arens, E., Huizenga, C., 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 45, 389-398, doi:10.1016/j.buildenv.2009.06.015.
11. Filingeri, D., Havenith, G., 2015. Human skin wetness perception: psychophysical and neurophysiological bases. Temperature 2, 86-104, doi:10.1080/23328940.2015.1008878.
12. Bröde, P., 2018. Predicting wetness perception on car seats, Peer-reviewed extended abstracts submitted to 12th International Manikin and Modelling Meeting (12i3m). Zenodo, St. Gallen, Switzerland, pp. 1-2, doi:10.5281/zenodo.1404460.
13. Diggle, P.J., Liang, K.-Y., Zeger, S.L., 1994. Analysis of longitudinal data. Oxford University Press, New York.
14. Bröde, P., Griefahn, B., 1994. Physiologic effects of heat during simulated car driving, in: Jürgens, H.W. (Ed.), Proceedings of the Second International Congress on Physiological Anthropology. University of Kiel, Kiel, pp. 118-121.
15. Bröde, P., Griefahn, B., 2005. Factors in the use of car seat ventilation, in: Holmér, I., Kuklane, K., Gao, C. (Eds.), 11th International Conference on Environmental Ergonomics. Lund University, Ystad, Sweden, pp. 491-494.
16. Cabanac, M., 1971. Physiological Role of Pleasure. Science 173, 1103-1107, doi:10.1126/science.173.4002.1103.
17. Parkinson, T., de Dear, R., 2014. Thermal pleasure in built environments: physiology of alliesthesia. Building Research & Information 43, 288-301, doi:10.1080/09613218.2015.989662.
18. Schmidt, C., Wölki, D., Metzmacher, H., van Treeck, C., 2018. Equivalent Contact Temperature (ECT) for personal comfort assessment as extension for ISO 14505-2, in: Brotas, L., Roaf, S., Nicol, F., Humphreys, M. (Eds.), 10th Windsor Conference - Rethinking Comfort. NCEUB, Cumberland Lodge, Windsor, UK, pp. 454-469.