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Weighting of climate parameters for the prediction of thermal comfort in an aircraft passenger cabin

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ABSTRACT

In many approaches to the analysis and description of passenger thermal comfort, temperature is the most important determinant. This is rather a restrictive view, as there are other climate parameters like humidity and air movement that influence the passengers' comfort as well. In the present study, objective and subjective data were used to predict the comfort evaluation of air temperature, humidity and air velocity. The aim was to analyse the relative weights of the climate parameters for the prediction of overall thermal comfort. In three studies empirical data were gathered from 169 subjects. An aircraft mock-up of a Dornier 728 was used as test facility, where different climate scenarios were realised by varying the mean cabin temperature (21.5 °C–26 °C, mean air velocity approx. 0.15, humidity max. 30%). Climate parameters were measured via appropriate sensors and rated regarding their intensity and comfort by the subjects via questionnaires.

Statistical models were developed that describe the non-linear and linear relationships between the three climate parameters and their respective comfort ratings. It was found that subjective ratings explained more variance than objective measurements. Regression analyses indicated that air temperature had the largest weight for comfort predictions, but humidity and air draught also had significant effects and should not be neglected. The present results demonstrate that thermo-comfort-models which include subjective data and account for different climate parameters and their interrelations should be considered in the development of aircraft cabin interiors.

1. Introduction

For the development of measures that can improve the thermal comfort of aircraft passengers, there still is a need for valid prediction models. Up to the present, models describing general indoor climate comfort are employed and analysed regarding their validity for the prediction of comfort in the aircraft cabin. The current research aims to identify and analyse comfort determining factors and their interrelationships, to assess the relative importance of different parameters or to develop practical thermal comfort models. In their overview, Streblow, Müller, Gores and Bendfeldt [1] classified the existing thermal comfort models in two categories: models using a statistical approach and models using a physiological approach. While statistical models mostly describe mathematical relationships between environment and subjective perceptions (e.g. Predicted Mean Vote, PMV [2]), physiological models provide differential analyses of physical processes – e.g. heat transfer – in special climate conditions [3,4]. Both approaches have been criticised with regard to their application in the aircraft context: As there are inhomogeneous and transient climate conditions in an aircraft cabin (like vertical and horizontal temperature differences and multidimensional turbulence), statistical models, which focus on stationary conditions, have only little predictive power [5]. Physiological models require large datasets for the description of physical processes and state of health, which usually are difficult to assess. Moreover, psychological research has shown that the analysis of basic physiological processes is not sufficient when predicting actual perceptions or behaviour [6].

1.1. The value of subjective ratings for the prediction of thermal comfort

In statistical and physiological approaches, subjective ratings are systematically combined with objective climate data to provide

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valid comfort predictions in thermally complex situations [1,7]. Fanger [2] established the assessment and usage of subjective ratings for comfort predictions in indoor climate research. In his PMV index, the climate perception rating, which is made on a 7-point-scale from cold to hot (−3 cold to +3 hot) is linked with a satisfaction rating. Zero is neutral and represents the greatest satisfaction with the indoor climate, while large deviations (≥2 on the rating scale) are categorised as causing dissatisfaction. An overview of empirical and theoretical studies that illustrate the methodological limitations of the PMV can be found in Refs. [8,9]. One of the difficulties identified was that individual climate preferences like satisfaction with warmer or colder temperatures cannot be expressed [8,10].

The general value of subjective ratings over and above their usage within the PMV has been demonstrated empirically: Fransson, Västfjäll and Skoog [11] confirmed the impact of subjective in addition to objective data for the prediction of the perceived comfort of the indoor environment in a hospital setting. For the aircraft context, incremental effects of subjective climate evaluations compared to objective temperature measures were found when predicting thermal comfort in an aircraft cabin [12].

1.2. Weighting of climate parameters

Indoor climate is mainly determined by the parameters temperature, air movement and humidity. For all three parameters, recommendations and standards are available concerning the development of comfortable climatic conditions based on previous research [13].

Temperature is a crucial parameter for climate sensations. This is obvious as temperature is the main determinant of Fanger's PMV, in which it is used to predict subjective temperature ratings and comfort evaluations. As the PMV was used in many thermal comfort studies, many findings and validation studies considering temperature are available [14]. Comfort standards for the indoor climate (ISO 7730 [15]) or for the aircraft cabin (ISO 4618 [16]) are based on the Fanger model and thus also on the indoor temperature.

The effect of air movement on thermal comfort sensations has been taken into account since the 1970s. Studies have focused on global as well as local air flow – for example the impact of air draught on people's heads has been analysed [17,18]. Regarding the relation of air temperature and air movement it was found that people became more dissatisfied with the thermal situation in conditions where air velocity was increased while air temperature was reduced [19]. As a result of such studies, Fanger and Christensen [19] developed a draught equation that described the relationship between mean air velocity and air temperature and the percentage of people dissatisfied. This chart was supplemented with the effect of turbulence intensity and adopted as a standard in ISO 7730.

Nagda and Hodgson [20] gave an overview of studies dealing with the relevance of humidity in the context of thermal comfort and subjective well-being. The authors specified the relationship between dry air and climate satisfaction for different temperature levels and reported little comfort in aircraft cabins where very low humidity levels (<20%) during cruise flight are common. From their results they suggested increasing the humidity level by 10% to improve thermal comfort. The idea to increase humidity in aircraft cabins was supported by Strøm-Tejsen, Wyon, Lagercrantz and Fang [21], even though they could not confirm an improvement in thermal comfort based on their research in an aircraft cabin mock-up.

Until now, little research is available dealing with the combined effect of several climate parameters on thermal comfort and their interrelationships in aircraft cabins. Grün, Hellwig, Trimmel and Holm [22] considered the concurrence of temperature, humidity, noise and pressure for the thermal comfort in an aircraft cabin. The relationships between temperature, noise and thermal comfort were confirmed, while humidity had no effect in the prediction equation. All in all, their results suggest that a more holistic approach to further research on thermal comfort is required. With regard to indoor climate, Fang, Wyon, Clausen, and Fanger [23] analysed the impact of temperature and humidity on perceived air quality, sick building syndrome and office work. They found that decreasing indoor temperature and humidity compensated for negative effects resulting from a reduction of the ventilation rate in offices. Alm et al. [24] provided evidence for the dominance of temperature in the context of air quality and sound pressure level when identifying determinants of thermal discomfort.

1.3. Aims and objectives

This study develops statistical models for the prediction of thermal comfort in the aircraft cabin. Objective climate parameter measurements and subjective climate parameter judgements were taken into account to predict climate comfort from a psychological perspective. With reference to the studies [10] and [12] discussed earlier it was hypothesised that subjective judgements are better predictors for thermal comfort than objective measurements.

In a further step, the relative importance of different climate parameters for the prediction of overall climate satisfaction was examined using objective and subjective predictors. Of peculiar interest was establishing the relative importance of air temperature, air velocity (or air draught) and humidity and their interrelationships. Based on previous findings, air temperature was hypothesised to have the greatest weight in the prediction equation while humidity was expected to have the smallest weight.

2. Method

Three empirical studies were performed. In order to gather a broad dataset, six different climate scenarios corresponding to cruise flight conditions in a commercial passenger aircraft were developed by varying the mean cabin temperature. The studies were carried out in an aircraft mock-up of a Dornier 728, which is a test facility of the DLR e.V. The mock-up is a single aisle jet with a cabin interior that is fully equipped. It has 70 seats in 14 rows and an environmental control system that allows adjusting air temperature, air velocity and humidity. Mixing air is provided through 64 air inlets at the cabin ceiling and no individual adjustments (e.g. via nozzles) are possible. As the cabin pressure cannot be controlled, air pressure inside the mock-up corresponds to ground conditions.

2.1. Participants

The recruitment of participants was undertaken with the help of a service contractor via online panel. Sixty subjects participated in Studies 1 and 2; in Study 3 only 50 seats could be used by participants as a result of the measurement equipment in the cabin. Altogether, data from 169 subjects were available for analysis (one dataset was lost during the assessment).

In each study, 50% of the subjects were male ($n = 84$ in total) or female ($n = 86$) respectively. The subjects' age ranged between 18 and 54 years ($M = 34.9$, SD = 9.3), their height between 152 cm and 196 cm ($M = 173.9$ cm, SD = 9.1) and their weight was between 42 and 140 kilos ($M = 76.6$, SD = 17.8). A group of 12 participants (3.5%) had no experience of flying as a passenger in a commercial aircraft.