VENTILATION IS NOT THE SAME AS VENTILATION – THERMAL COMFORT IN THE AIRCRAFT CABIN

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Abstract

In the research project Comfortable and Silent Cabin+, thermal comfort was analyzed in an aircraft cabin mock-up of a Dornier 728. Two realistic climate scenarios were realized as test conditions: cruise flight and climb flight, with different temperatures and air flow rates each. Objective and subjective data concerning several climate parameters and comfort perceptions were assessed by means of physical measures and questionnaires. In sum, 280 subjects participated in four investigations. Due to a differentiated measurement design, objective data concerning the local air stream could be gathered for ten seats only.

Our results confirm that the air flow at different parts of the body and at different seats is characterized by different velocities – and perceived as different by the subjects. Altogether, the stronger the air flow felt in cruise flight, the less comfortable it is rated ($r = -.42$, $p < .01$, $N = 70$). In climb flight, more air flow tends to be more agreeable ($r = .16$, n. s., $N = 70$). The correlation between air velocity and subjective ratings is not as clear. Combining objective and subjective data seems to be promising when predicting thermal comfort: more than 70 % of variance can be explained in path models. Objective data can be complemented significantly by subjective perceptions when predicting thermal comfort and should be taken into account in cabin design.

Keywords: aircraft, air draft, air velocity, subject test, thermal comfort

1 Thermal comfort in the aircraft cabin

Thermal situations can be described by parameters like air stream, temperature, air quality and humidity, which can all be measured using adequate sensors. From these, the comfort a situation provides can be inferred. But which meaning does such an inference have for the thermal comfort perception of individuals?

According to ISO 7730, thermal comfort is defined as "the state of mind, which expresses satisfaction with the thermal environment" (p. 4) – a definition directly relating to Fanger's PMV-model (Fanger, 1972). Fanger's approach has been validated and approved many times. But in a recent review, van Hoof, Mazej and Hensen (2010) summarize that despite its widespread use, the weaknesses of the model concerning e. g. the validity of the whole scale or its sensitivity to between-individual differences in optimal thermal conditions have been illustrated in some field studies. Further models have been developed that were intended to improve comfort predictions in more complex climate situations and to integrate moderating factors like outdoor climate, adaptive behavior or situational factors (cf. Nicol & Humphreys, 2002). For example Zhang (2003) developed a differentiated and widely used human model to predict local and overall thermal sensation and comfort. It is based on subject tests that were performed under non-uniform and transient conditions in a laboratory. Human comfort models like Zhang's which have been empirically confirmed can provide valuable information concerning the evaluation of the cabin situation regarding thermal comfort.

Aircraft cabins provide a special climate situation for the passengers due to surrounding conditions. In addition to barometric pressure, certain architectural conditions such as equipment, concavity of the ceiling or arrangement of air in- and outlets complicate the situation. Moreover, the climate is influenced by local turbulences and characterized by transient thermal conditions. Thermal loads are caused by solar radiation, electrical equipment on board and the heat dissipation of the passengers. For aircraft industries the design task is to ensure security and thermal comfort for the passengers by laying out the air conditioning system adequately. The objective is to guarantee agreeable temperatures and a high air flow exchange rate for each individual passenger without generating too many disturbing effects like air draft.

Since experimental investigations of cabin layouts with real passengers are expensive and time consuming, only few studies have been published so far. Computer simulations are frequently-used to gain comfort statements (e. g. Computational Fluid Dynamics, CFD). Rütten, Konstantinov and Wagner (2008) demonstrated that data obtained in numerical flow simulations can be successfully validated for example by high resolution thermography. CFD results reflect certain flow features that are quite similar to those found in experimental tests.

In the research project Comfortable and Silent Cabin+ we were aiming at developing a thermal comfort model consisting of objective and subjective data. A multidimensional measurement model was designed for data gathering. Objective and subjective parameters were combined theoretically to provide a thorough basis for the analysis of thermal comfort in the aircraft cabin (Fig. 1): Climate conditions like temperature or strength of air stream can be operationalized by physical parameters. They have an effect on the passengers in an aircraft. The passengers' reactions to the climate are influenced by personal characteristics and can be measured by questionnaires. From these, thermal comfort statements can be inferred.

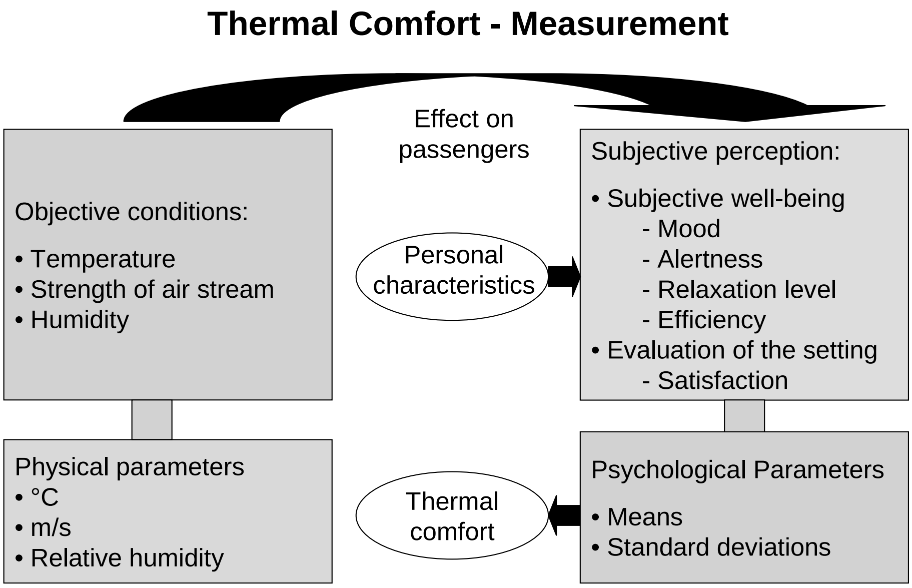

Figure 1. *Thermal comfort measurement model*

The focus of this paper is on strength of air stream and its relevance for comfort evaluations. It is hypothesized that air flow is perceived as different by the subjects depending on body part, seat line and the climate situation they are in. Further, subjective ratings should provide information beyond objective data measured by physical parameters only.

2 Method

Four human subject tests were conducted in an aircraft mock up of a Dornier 728 between December 2007 and September 2009. In this paper, data of the third test in May 2009 is analyzed, where differentiated objective data could be gathered. For further results see Marggraf-Micheel, Piewald, Winzen and Berg (2010).

The Dornier 728 is a single aisle jet with a complete cabin interior comprising 70 seats in 14 rows; two seats on the right and three on the left side of the cabin. Its air conditioning system is fully operative and provides mixed air through 64 inlets. These are arranged in two lines along the ceiling and below the overhead bins. After circulation in the cabin, air leaves the cabin through 24 air outlets located at the cabin floor. Only the pressure situation in the mock up cannot be varied and is equal to ground conditions.

2.1 Experimental design

As test conditions, two climate scenarios inspired by real flight situations were realized in the cabin: climb flight and cruise flight. These specific air ventilation scenarios were achieved by adjusting volume flow ratios, air humidity and temperature. Table 1 illustrates the experimental design and nominal values for the scenarios that could mostly be implemented during the experiment. Mean temperature measured inside the cabin was 22.9°C for cruise flight and 25.2°C for climb flight. Humidity inside the cabin was higher than intended: during cruise flight an average of 22.9 % relative humidity was measured, during climb flight 36.3 %. Mean air velocity measured in cruise flight was 0.17 m/s and in climb flight 0.15 m/s. Both scenarios were presented twice to the subjects in an alternate order to avoid order related effects.

Table 1. *Experimental design and nominal values for the climate scenarios*

Neutral	Climb	Cruise	Cruise	Climb
Climate not controlled	25°C 25 % humidity 540 l/s	22°C 18 % humidity 660 l/s	22°C 18 % humidity 660 l/s	25°C 25 % humidity 540 l/s

2.2 Instrumentation

Measurement instrumentation was installed on different spots inside the cabin in order to gather physical data concerning climate parameters. Temperature and humidity were measured by appropriate sensors in the centre of the cabin and on 40 passenger seats. Air velocity was determined by special sensors on ten seats: Thirteen sensors were adjusted in front of each seat to capture the air stream next to different parts of the body: both feet, knees, arms, shoulders and ears were covered as well as breast, nose and neck. Since the subjects' mobility could not be guaranteed given the number and arrangement of air velocity-sensors, air stream had to be determined subsequently in a replication of the test scenarios with dummies. Each dummy generates an adjustable heat load between 70 W and 95 W, reflecting the thermal load of a passenger in an aircraft cabin.

Subjective data were assessed by established psychological questionnaires. The test quality of these surveys has been proven to be satisfactory for use in cabin research (see Marggraf-Micheel & Jaeger, 2007). Scales to measure the subjects' perception and evaluation of the climate situation were considered for the climate parameters air stream, temperature, humidity and air quality. Further, the subjects' global and local comfort was assessed.

2.3 Subjects and procedure

In each investigation, 70 subjects participated. In May 2009 we tested 35 female and 35 male students, ages 19 to 29 (M = 23.8, SD = 2.61), of different fields of study. Their height was between 1.58 m and 1.92 m (M = 175.8, SD = 8.6), their weight between 50 and 95 kilos (M = 70.6, SD = 10.99). All subjects were German native speakers and had not participated in a similar study before. Most of them had experienced at least one to five real flights in the past. The subjects' clothes were standardized – they had to wear long sleeve shirts and long trousers; no scarfs, boots or turtle neck collars were allowed (see Fig. 2).

Figure 2. *Human subject test in the Dornier 728*

Each climate scenario was presented to the subjects for twenty minutes. After this exposure time, subjects had ten minutes to fill out the questionnaire while the climate remained unchanged. During the whole experiment, all questions had to be answered five times; the first time was for training purposes and to get a baseline of climate judgments. The adjustment of the climate scenarios from climb to cruise and from cruise to climb took 25 minutes, hence the subjects stayed in the cabin for about three hours. A movie was shown to entertain them, except when they answered the questionnaire. Snacks and water were provided.

3 Results

Mean comfort values were calculated for each climate condition from both runs to analyze comfort differences between body parts and seat lines. Results concerning objective data are reported for ten cases; subjective data could be gathered and analyzed for all 70 subjects in the cabin.

3.1 Body parts

Figure 3 shows the mean values for air velocity measured at different parts of the body and the corresponding subjective ratings. Rating scales went from 1 = “no air draft” to 7 = “strong air draft” for the perception and from 1 = “very uncomfortable” to 5 = “very comfortable” for the evaluation judgment.

The lowest air speed is measured at both lower arms and knees; the highest at the ankles and at the head. All differences greater than or equal to Δ = 0.05 between body parts are significant. Even though dissimilar air flow rates were aspired, velocity rates near to body parts differed only slightly for cruise and climb flight according to objective measures.

As can be inferred from the subjective data shown in Figure 3, generally little air draft is perceived (M = 1.99, SD = 0.4). The subjects’ perception of air stream differed depending on the climate situation ($F_{(1, 69)} = 68.2$, $p \leq .00$): In cruise flight, subjects sensed more air flow at all parts of the body; especially at the ankles, the upper legs and

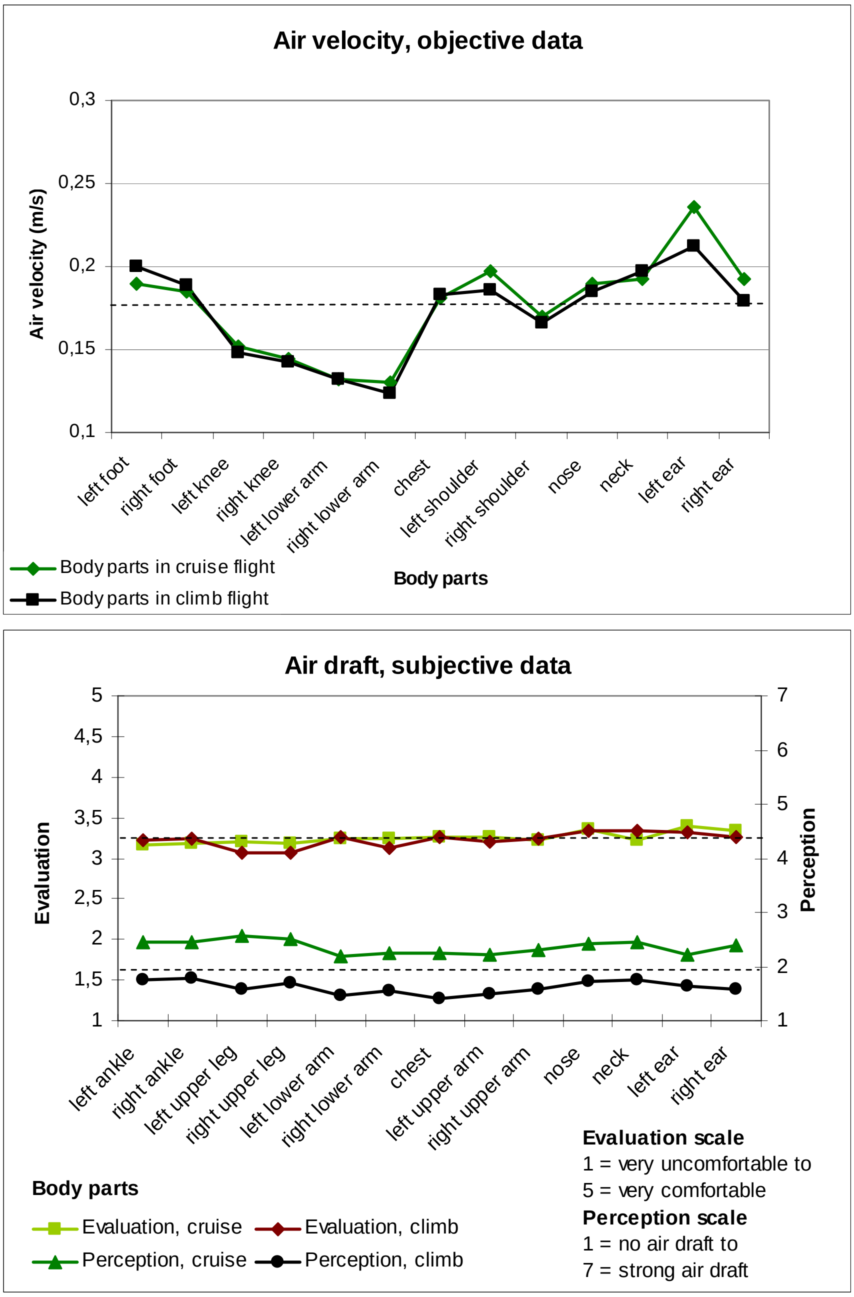

Figure 3. *Objective and subjective data of air flow per body part*

the neck. The least air flow was perceived at the chest and the left side of the body. Differences are meaningful with $F_{(5.1, 349.2)} = 2.07$ ($p \leq .10$). The evaluation of the air flow situation is generally positive (M = 3.26, SD = 0.08), but differs notably for the body parts ($F_{(7.1, 490.2)} = 3.99$, $p \leq .00$): It is least comfortable at the upper legs – especially in climb flight – but rather comfortable at the head. The stronger the air draft felt in cruise flight, the less comfortable it is rated ($r = -.42$, $p < .01$), while in climb flight the perception of stronger air draft tends to be evaluated more agreeable ($r = .16$, n. s.).

3.2 Seat line

The data set was further analyzed by seat line. In Figure 4 mean values of air velocity are illustrated for each seat line lengthwise, seen from the cockpit. On the right side of the cabin, air stream is slightly stronger in cruise flight than in climb. Only weak velocities are measured at the left window seats, stronger velocities can be found at the middle row and at the aisle, mainly on the left side. Differences in means greater than or equal to Δ = 0.03 are significant.

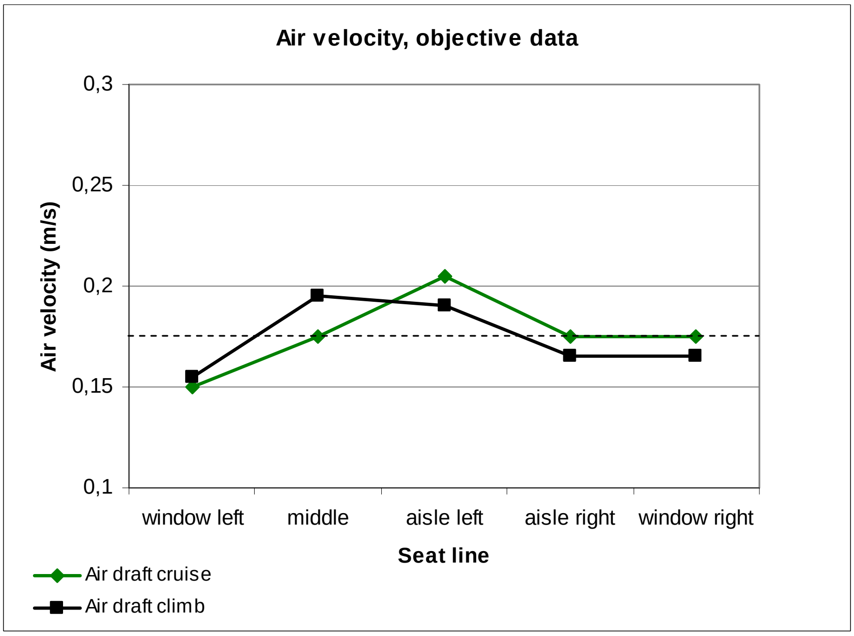

Figure 4. *Objective data of air flow per seat line*

Subjective ratings indicate that more air draft is perceived in all seat lines during cruise flight conditions. Just as can be inferred from the objective measures, little air stream is experienced by those subjects

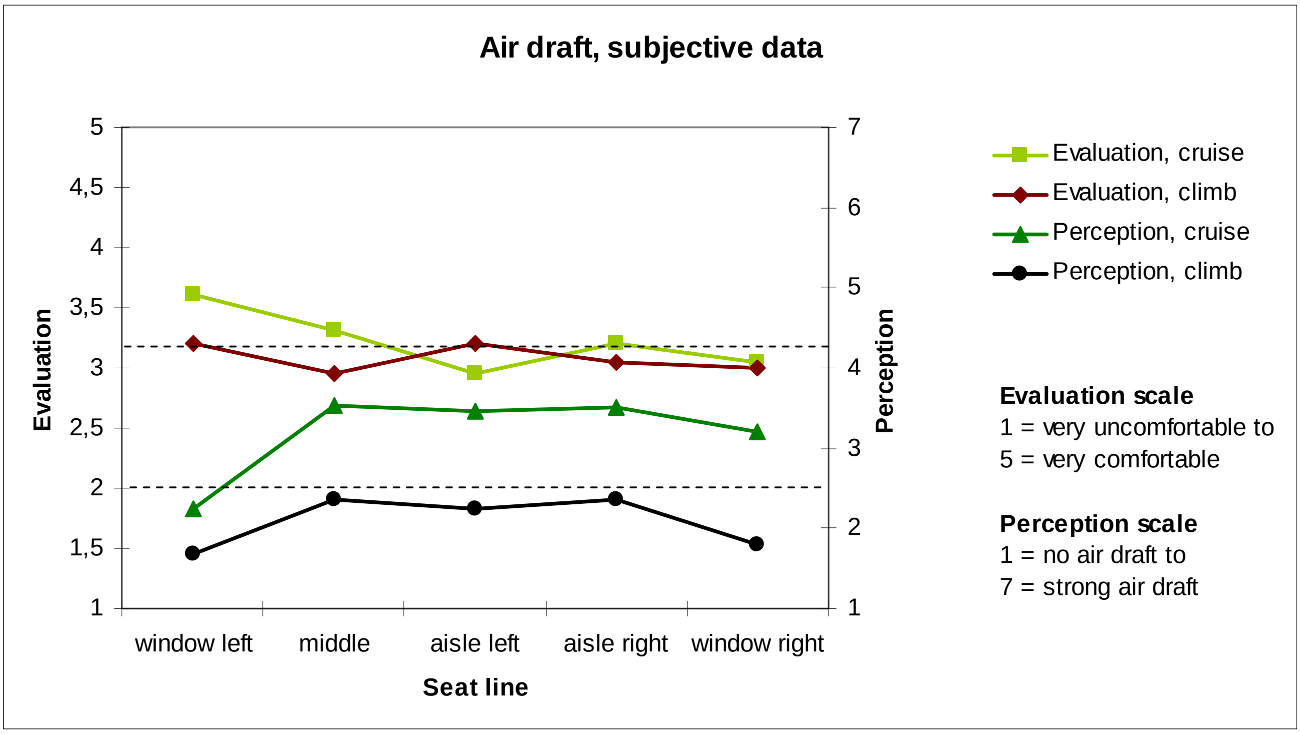

Figure 5. *Subjective data of air flow per seat line*

who are sitting on the window seats. Differences between the five seat lines are significant ($F_{(4, 65)}$ = 4.26, p < .01). Concerning the comfort evaluation, no significant difference can be identified ($F_{(4, 65)}$ = 0.81, n. s.). However, air draft is rated more agreeable at the window seats on the left side of the cabin, where little air draft is perceived.

3.3 Combining objective and subjective data for comfort predictions

The relation between objective and subjective data was analyzed by correlating the data in the first instance. As can be inferred from the results reported above, there is a certain correspondence between objective measurements and subjective judgments. Spearman's rho correlation coefficient between air velocity and subjective perception is r = .44 (n. s.) in cruise flight and r = .64 (p < .05) in climb flight. Higher air velocities are thus perceived as stronger air draft. The subjective evaluation is related to air velocity with r = -.19 (n. s.) in cruise and r = .54 (n. s.) in climb flight. This corresponds to the results for subjective data only: more air speed is less comfortable in cruise flight and the more comfortable in climb flight (see 3.1). The correlation of objective data with a general comfort rating was r = .29 (n. s.) in cruise and r = .52 (n. s.) in climb flight, which means that generally, higher air velocities tend to contribute to more thermal comfort.

In a further step it was analyzed in how far a combination of both data sets contributes to the prediction of comfort ratings. In this context, path models were calculated. Although the sample is rather small for this procedure, all statistical requirements are fulfilled. Figures 6 and 7 show the path models for both climate scenarios. All variables are illustrated as rectangles. The amount of variance that can be explained in a variable is indicated on its right upper corner. Arrows represent the relationship between two variables; the corresponding values indicate the strength and the direction of the relation given all variables in the model (= regression weights). Variables e1 to e4 represent non-systematic errors that have to be generally assumed in psychological testing.

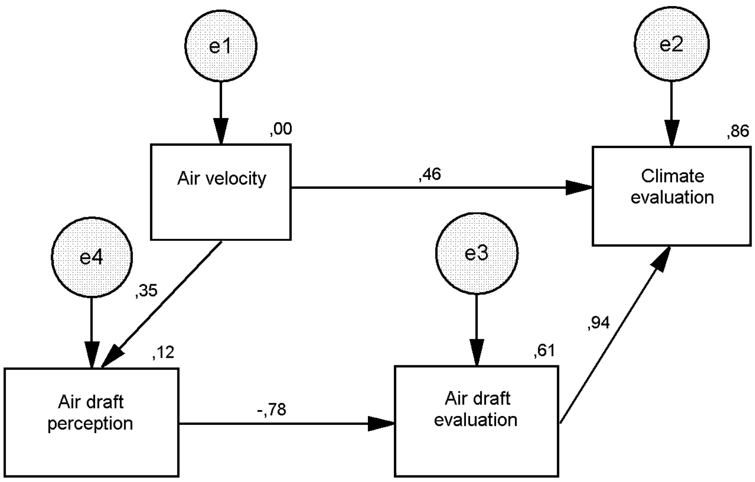

Figure 6. *Path model of air draft in cruise flight*

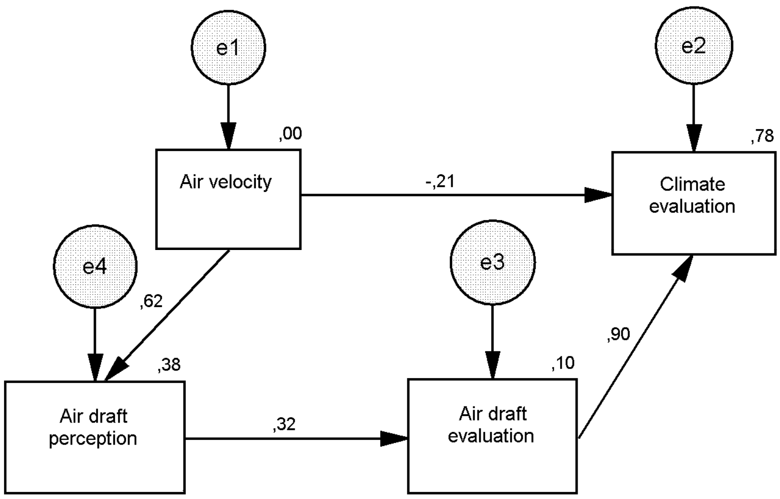

Figure 6. *Path model of air draft in climb flight*

The statistical indices confirm the model fit. For cruise flight, Chi square is 1.2 (df = 2, p = .55); for climb flight it is 0.5 (df = 2, p = .77), which indicates a very good fit of both models with the empirical data. Most of the variance in the subjective climate evaluation can be explained; 86 % in the cruise case, 78 % in climb. The most important predictor is the air draft evaluation, which is directly influenced by the air draft perception. This relation is negative in cruise flight and positive (but not significant) in climb flight, which corresponds to the previously mentioned bivariate correlations. The relation between air velocity and air draft perception corresponds to spearman's rho in height and direction for both scenarios, too, but is significant in climb flight only. Air velocity is directly related to the climate evaluation in cruise flight and can explain 21% of the variance. The relation for climb flight is not as clear, the coefficient is rather small and the negative pole of the regression weight (n. s.) does not correspond to the previous results.

4 Discussion

In our study we analyzed objective and subjective measurements of air flow during a cruise and a climb flight scenario in a Do 728 mock up. Body parts and seat line were considered as moderator variables and objective and subjective data were combined in path models to predict thermal comfort.

Different values for air velocity were measured at different parts of the body; deltas were similar in both climate scenarios. Especially in the sitting height, stronger air velocities were measured compared to feet or head. Subjects perceived significantly more air draft in cruise flight than in climb. Air draft was rated as rather comfortable at almost all body parts in both scenarios, but more air draft induced lower comfort ratings in the colder climate cruise. The analysis of the seat lines leads to similar results. More air draft is felt by the subjects in cruise flight, especially in the three middle rows (middle, aisle left and right). The least air draft in the left window seat line is evaluated as being most agreeable, especially in cruise flight. As the cruise scenario was the colder one, these results confirm that the rating of air draft perception is not solely depending on air velocity but also coincides with the supply air temperature.

The combination of objective and subjective data confirmed the validity of subjective measures: higher air velocities are perceived as stronger air draft. The air draft perception influences the comfort evaluation regarding air draft – during the colder cruise case, the more air draft is perceived the less comfortable it is rated. While during the warmer case climb, the relation is positive: the more air draft is experienced, the more comfortable it is rated. The air draft evaluation has a strong effect on the general comfort rating. Air velocity alone can explain a certain amount of variance, 8 % and 27 % respectively for cruise and climb flight (according to the correlation coefficients), but the prediction is improved significantly to more than 75 % in both climate scenarios by taking into account subjective data as well. Personnel characteristics, expectations and preferences influence the perception and evaluation of climate conditions (see also Marggraf-Micheel et al., 2010). Limitations can be seen in the fact that the test situation in an aircraft mock up does not exactly represent real flight conditions: The climate scenarios could not be realized just as planned; outside temperature and pressure could not be varied accordingly. It has to be discussed if our results are applicable to passengers on real flights. Evidence suggests that there is an effect of barometric pressure on apparent temperature in high altitudes (McFarland, 1937), but it seems to be of negligible strength in aircraft cabins, where the climate is controlled. Effects range from -0.1 to +0.4 K according to Steadman (1979).

Despite these caveats, our results provide valuable information for practical purposes. In cabin design, engineers are advised to take into account passengers' demands when conceptualizing new – energy-saving – kinds of cabin interior: in colder climate situations like cruise flight, less air draft, especially in the sitting height, improves thermal comfort. In rather stifling climates like climb flight, more air draft contributes to higher comfort – as long as it is not exceeding a certain threshold.

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