Impact of different ventilation strategies on aircraft cabin air quality and passengers' comfort and wellbeing – the ComAir study

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Indoor air quality can affect occupants in numerous ways. Especially carbon dioxide (CO_2) and volatile organic compounds (VOCs) have been debated in their effects on health, well-being, and cognition of people. Aircraft cabins present indoor environments with distinctive features, where passengers are exposed to a mixture of outside and recirculated air. They include conditions such as high occupant density, inability to leave the environment, low relative humidity and need for pressurization. The ComAir study, funded by the Clean Sky 2 Initiative of the European Union, aims to investigate the impact of reducing outdoor air intake in the total volume of air supplied on cabin air quality and passengers' wellbeing. The main experiment of the study uses a 2 ('occupancy') X 4 ('air ventilation regime') factorial design with stratified randomization of participants. Occupancy denotes the number of people in the aircraft (half vs. full) and varies the psychological important wellbeing factor of proxemics. The four air ventilation regime levels are: Baseline with typical aircraft airflows regimes per person, ASHRAE 161 requirement (standard recommendation), ASHRAE 161 half (half of the recommended flow), and a recirculation regime with a target CO_2 concentration close to regulatory limit. This paper presents the background and experimental procedure of ComAir and gives some preliminary results on environmental conditions and subjects' wellbeing and health under the baseline air ventilation regime.

Nomenclature

β	=	value of statistical beta error
cfm	=	cubic feet per minute
EMM	=	estimated marginal means from controlled analysis of variance
η^2	=	Eta-squared, measure of effect size for use in analysis of variance

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F	=	test value for analysis of variance
f	=	Cohen's f, measure of effect size for use in analysis of variance
N	=	sample size, number of participants
ppm	=	parts per million
p	=	level of significance
r	=	Pearson correlation coefficient
SD	=	standard deviation

I. Introduction

Indoor air quality (IAQ) is one of the important factors that affect occupants in numerous ways. IAQ can be affected by different gases, such as carbon monoxide and volatile organic compounds (VOC), as well as different particulates, microbial contaminants (mold, bacteria) that can, in vast amount, induce adverse health conditions[1]. According to ASHRAE guidelines[2], people spend about 80-90% of their times indoors, such as homes, gyms, schools, work places, transportation vehicles. Therefore, IAQ has a significant impact on a range of comfort and health-related effects, as well as quality of life in general. Poor indoor air quality can be harmful for all people, particularly for vulnerable groups such as children, young adults, the elderly, or those having chronic respiratory and/or cardiovascular diseases[1].

In recent years, the number of people travelling by commercial aircraft has increased. The aircraft cabin is similar to other indoor environments where people are exposed to a mixture of outside and recirculated air. However, it is different in many respects as well, such as the high occupant density, the inability of occupants to leave the environment, low relative humidity and the need for pressurization[3,4]. All of this can produce negative health effects, such as dry mucus membranes, irritation of eyes, nose and respiratory tract and associated symptoms, dizziness, fatigue, headaches and sore throat, among others, which may continue even after the exposure[5]. Consequently, passengers' and cabin crew's comfort and wellbeing can be negatively influenced by cabin air.

Comfort and wellbeing are two multidimensional phenomena, mutually independent but closely associated. The term wellbeing encompasses various forms in which people experience and evaluate their lives positively[6]. There are two main, established approaches to conceptualizing wellbeing - hedonistic and eudaimonistic. Due to its long-term, personality-development perspective the eudaimonistic approach is not suited for a short-term experimental approach. Hence, the hedonistic approach is important and operationalized as subjective wellbeing. It includes two components: affective, which refers to experience of positive and negative feelings; and cognitive, which refers to the overall judgment of life satisfaction. In studying aircraft cabin air cognitive component encompasses satisfaction with air quality and other environmental conditions during the flight simulation. Positive affect of the affective component includes feelings such as serenity, relaxation and, among others, comfort, pointing out the association of wellbeing and comfort.

Comfort is a multifaceted construct with a number of aspects describing this short-term wellbeing phenomenon and the factors influencing it. There are several different models looking at comfort and related conditions like satisfaction with the environment[7]. Originally, the concept of human comfort has mostly been used to study physical or physiological sensation and perception of discrete environmental stimuli from one's immediate surroundings to find the point where the human body feels comfortable (that is, relaxed, free from constraint, pain, stress, or tension). However, a number of recent studies challenge this restricted view and show the importance to focus not only on simple associations between environmental stimuli and bodily sensation but also the complex interaction with a number of other person- and environment-related aspects[8,9,10]. All these aspects generate a person–environment fit - the degree to which individual and environmental characteristics match[11], indicating a good fit might then produce positive outcomes like satisfaction, comfort, and wellbeing.

For instance, proximity of other people is one aspect worthwhile of addressing in indoor air quality. Edward T. Hall[12] defined proxemics as the "interrelated observations and theories of human's use of space as a specialized elaboration of culture". The term refers to the perceived relationship between the social and physical distance in human interactions[13]. Proxemic behavior, i.e. the use of space affects interpersonal communication and contributes to evaluating how people interact with each other in daily life, as well as how they organize their space. According to Hall[12], the most important aspects of proxemics are the invasion of private space by others and ensuing violation of the need for privacy that not only leads to uncomfortable feelings, unease and strain but also has an impact on behavior, like e.g. compensating for too much physical closeness by cutting back verbal interaction. A recent study showed that invasion of personal space, caused by both physical factors (e.g. physical contact with humans or objects) and sensory factors such as noise, smells or unwanted eye contact, can have a negative impact on passenger comfort[14]. In addition, Ahmadpour et al.[13] found that proxemics, operationalized as autonomy and control, and desire for privacy was one of the most important themes related to comfort in the cabin interior reported by passengers. Therefore, personal space should be taken into account in relation to comfort and wellbeing parameters of the passengers.

There is a growing body of research on aircraft cabin air quality, comfort parameters and health symptoms. Experiments included human exposure and investigated the impact of airflow makeup on contaminant concentration, perception of air quality and health-related symptoms[15]; including the evaluation of the impact of air purification technologies on chemical contamination of cabin air and comfort of passengers and flight attendants[16,17,18], the evaluation of air quality and thermal comfort of aircraft cabin at 69°, 74° and 79°F (20.6, 23.3 and 26.1 °C) [19], or simulations and measurements on dispersion and deposition of expiratory aerosols in a cabin mock-up[20,21]. All of these show rather divergent effects, that is, current state of research implies that it is worthwhile to further research cabin air quality parameters in relation to health symptoms, in order to deliver ventilation optimal for both passengers' and crews' health.

Although some aspects of comfort and perceived air quality have been studied so far, the amount of research on the wellbeing and comfort in association with air quality parameters is scarce. According to Ahmadpour et al.[13], existing literature has been mainly focusing on physical aspects of the environment, for instance sitting, acoustic or thermal comfort, or holistically on the significance of the cabin features to passengers' perceived level of comfort. This qualitative study with 158 participants identified eight comfort themes related to passenger's experience in the aircraft cabin[13]. Comfort was shown to be related to both physical wellbeing, as well as psychological, proxemics, satisfaction, pleasure, aesthetics, social as well as association to familiar experiences. Vink and colleagues[22] analyzed more than 10,000 internet trip reports and 153 passenger interviews to gather opinions about aspects, which need to be improved in order to design a more comfortable aircraft interior. The results showed clear association between comfort and legroom, and seat/personal space, among others. Rankin, Space and Nagda[23] carried out a passenger comfort survey with a major U.S. airline on 3630 respondents. The study found that seat comfort, flight smoothness, and air quality were the important determinants of passenger comfort. Furthermore, the European project "Ideal Cabin Environment " (ICE) evaluated the effect of air temperature, relative humidity, noise and pressure parameters on perceived comfort[24]. Interrelations of thermal comfort, temperature and noise were found. Additionally, thermal comfort was affected by low pressure when the background noise was at a lower level. The ICE project also examined health effects and wellbeing of passengers in an 8-hour flight simulation, at pressures equivalent to terrestrial altitudes of ground, 4000, 6000, and 8000 ft. The results showed no effect of oxygen saturation on reported wellbeing. In addition, low oxygen saturation, commensurate with low cabin pressures, was not associated with passenger discomfort or adverse consequences[25]. As demonstrated, all of these studies address specific parts of comfort and wellbeing in relation to various cabin environment parameters, while larger experimental studies with methodologically sound designs (RCTs) are (mostly) lacking.

II. Rationale

Measurement of air quality in aircraft cabins has been the focus of a number of studies conducted or commissioned by aviation authorities and environmental agencies[26,27,28,29,30,31]. Additionally, there are numerous studies researching indoor air quality in offices or schools as well as other isolated environments like submarines (see e.g. overviews by the German Working Group on Indoor Guideline Values of the Federal Environmental Agency and the States´ Health Authorities on CO_2[32] and on TVOCs[33]). However, the impact of air quality in terms of CO_2 and VOCs on wellbeing and comfort has been less often researched. Only few studies did this in a controlled way[34,35]; however, with small sample sizes and cross-over designs, and no conclusive results or clearly conceptualized outcome measure of wellbeing. Studies with large scale experimental (RCT) approaches with regard to CO_2 and VOCs are – to the best of our knowledge – missing completely. Results of existing research are heterogeneous especially with regard to "thresholds".

In line with the objective of the EU Joint Undertaking Clean Sky 2 and against this background the overall rationale of the ComAir study is to provide empirically sound results on the question if outside airflow rates in aircrafts can be reduced (with the consequence of increasing CO_2 and VOCs) without a negative impact on passengers wellbeing and comfort. If this is possible, the development of Adaptive Environmental Control Systems (AECS) developed under the Clean Sky 2 Adaptive Environmental Control program[36], with reduced outside airflow rates would help to lower fuel burn and therefore meet the objective of reducing emissions from air traffic.

Moreover, as air quality might only be one aspect of comfort and wellbeing perceptions (see for a ranking of comfort "driver" Bouwens et al.[37]), another previously neglected aspect of comfort will be researched – personal space in the sense of proxemics[12]. In comfort research, anthropometry is often mentioned as one of the most important influencing factor[37,38]; however, the effect is mostly assumed to depend on legroom, seat pitch, and cabin environment matching individual anthropometrics[39]. The psychological dimension of proxemics, like the perception of threat due to the invasion of privacy if a stranger comes to close, has not been researched so far.

III. Study Design and Methods

The ComAir study contains two different sequential experimental designs. Both experimental designs are monocentric, controlled in the experimental sense that there is a “normal” resp. good air quality situation, use a stratified randomization procedure, and were carried out in the Flight Test Facility (FTF) at the Fraunhofer Institute for Building Physics located in Holzkirchen south of Munich between November 2019 and January 2020. The Flight Test Facility consists of a 30 m long and 9.6 m diameter low pressure vessel, in which the front section of a former in-service aircraft (A310) is integrated. The mock-up contains the cockpit, front door/galley area and up to 10 rows of cabin economy class seating with overall 80 seats (Figure 2). In the underfloor area, the wheel box, avionics compartment, cargo, triangles and bilge are present. The mock-up has the ability to provide conditioned (temperature and humidity) HEPA-filtered recirculation air as well as outside fresh air. In the following sections of this paper only the main experimental design will be reported. The ComAir study was approved by the Ethics Committee of the Faculty of Medicine, Ludwig-Maximilians-University, Munich (ID: 19-256) and written informed consent was obtained from all participants.

A. Study design and sample size

The main experiment is a 2 (occupancy) X 4 (outside air rate) factorial design that is illustrated in Table 1. It takes into account cabin occupation and three elevated CO_2 target levels (based on recommendation from ASHRAE, 2007) estimated from outside air rates and a baseline measure. The baseline measure is derived from own in-flight CO_2 measurements conducted during business trips. Target values are given as sensor raw data, thus not pressure corrected. Different outdoor air supply regimes are studied at different passenger proximity. To study the effect of proximity, the cabin was fully or half occupied in different experimental conditions.

Table 1: 2X4 study design and estimate of sample size

	FACTOR: OUTSIDE AIR RATES			
	Baseline	ASHRAE 161 requirement**	ASHRAE 161 half	Max. CO_2
CO_2 target concentration in ppm	1200	1650	2750	4200
Expected TVOC in µg/m³	351	476	836	1307
Expected relative humidity in %	12	18	33	50***
Estimated outside airflow rate l/s/passenger	5.2	3.5	1.8	1.1
Recirc. airflow rate l/s/passenger	4.2	5.9	7.6	8.3
FACTOR: OCCUPANCY				
„fully booked“: 80-100% of seat capacity	1 session	1 session	1 session	1 session
“half booked”: 40-50% of seat capacity	2 sessions*	2 sessions	2 sessions	2 sessions
No. of subjects	150	150	150	150
			Total:	600

*to reach comparable sample sizes

**ASHRAE Standard 161 gives requirements for cabin ventilation like a temperature range between 18.3 and 23.9 °C, a stratification below 4.4 K and airflow velocities recommended below 0.2 m/s. The minimum outside airflow rate shall be 3.5 l/s/passenger and the minimum total supply air shall be 7.1 l/s/passenger. However, a minimum of 9.4 l/s/passenger is recommended. Recirculated air shall pass a HEPA file with a minimum collection efficiency of 99.97% for 0.3 micron particles.

***slight dehumidification in recirc air cooling expected

To ensure sufficient power for the study a participants sample size estimation was done. Existing studies show effects of air quality on health and wellbeing to be not existing, small or medium-sized[40,41]. At the same time there are only few studies for cabin air and no studies yet using increased recirculation air with incremental changes in condition under realistic pressure conditions. To minimize the risk of overlooking effects in this area, beta error should be lower than convention. Against this background, we calculated a-priori sample sizes for ANCOVA analyses (as preferred statistical procedure) defining alpha-error of 5% (convention), power of .85 ($1 - \beta$) and small to medium sized effects to be detected ($f=.15$; $\eta^2=.022$). With these setting a required overall sample size of N = 551 participants results. This corresponds to a minimum of 69 participants in each condition. Due to the occupancy factor, the "fully booked" conditions should therefore contain about 70 to 80 persons (max. capacity of FTF), whereas each "half booked" condition should be done twice with 35-40 participants each (Table 1) with an overall N of about 600 persons to give leeway for drop outs.

For results to be generalizable to real passengers, we aimed at a sample representative for flight passengers with regard to age and sex. The stratification variables were selected for two reasons: First of all, large-scale representative passenger data only contain very broad categories that can be used to describe the "flying population". That is, other potentially relevant data are not available. And secondly, with regard to outcomes sex as well as age have specific impacts. In general, most studies from different domains show lower comfort and wellbeing values for women compared to men, whereas older people usually report a higher wellbeing than younger people do, but might be more critically minded with regard to comfort.

Participants were allocated to the different experimental conditions via stratified randomization. That is, to make sure that differences can be traced back to the experimental conditions and not to problems in the distribution of control variables, participants are allotted by chance so that each experimental condition consists of the same sample distribution with regard to sex and age groups.

Besides stratification for sex and age, participants were screened in a three-steps procedure to ensure their fitness for flying, that is, as the experiments took place under low pressure conditions people needed to be reasonable healthy, without claustrophobia or fear of flying to participate. Moreover, all participants were blinded against the experimental condition they were allotted to.

B. Environmental exposure

Participants were subjected to four different outside air rates that were calculated in such a way that CO_2 stays below the limit values like maximum workplace concentration. VOCs were not manipulated but monitored and measured. Due to very low empty cabin VOC load, the cabin will mostly contain bioeffluents. Expected TVOC and relative humidity are presented in table 1.

For the cabin environment, the following settings were applied throughout the test campaign:

- Cabin air temperature: 23 °C
- Cabin pressure: 755 hPa (8000 ft.)
- Cabin light: Use of available standard light, day flight, Passenger Service Unit (PSU) light not operational
- Cabin noise: 74 dBA representative flight engine noise through loudspeakers

The outside air supply was controlled to maintain today's requirements and lower outside airflow rates. ASHRAE 161 states a minimum requirement for outside air flow of 3.5 l/s (7.5 cfm) per passenger and a recommended total airflow rate of 9.4 l/s (20 cfm) per passenger. Recent work by Persily and DeJonge (2017) estimate the average CO_2 production rate for sitting office work (1.4 met) at 0.0048 l/s whereas lower physical activity of 1.0 met leads to a CO_2 production of around 0.0035 l/s. Assuming an outdoor CO_2 concentration of 380 ppm during cruise, this would result in a cabin CO_2 level of 1380 to 1751 ppm. Own measurements in operated aircraft cabins reveal that lower CO_2 concentrations of about 1200 ppm (not pressure corrected) are typical for aircrafts. This suggests that 4.2 to 5.2 l/s per passenger of outside air rate is a more realistic baseline. The total airflow in the cabin was maintained at constant 9.4 l/s/passenger throughout the test conditions (as recommended by ASHRAE) by increasing the rate of air recirculation. Calculations in Table 1 are based on a span of subject activity (1.0 – 1.4 met) and the more realistic outdoor air CO_2 concentration of 450 ppm at FTF site. VOC and humidity levels adapt according to the outside airflow rate and are expected to correlate with the CO_2 level.

For each test, an experimental duration of about 4 hours in the cabin and an exposure to experimental air quality conditions of 170 minutes was targeted. Especially at low fresh air supply rates, the build-up time increases. Test sequence was timed accordingly for every experimental condition and in a close feedback loop with environmental conditions to ensure comparability (see Figure 1).

C. Test sequence

As a number of different parameters on wellbeing, comfort, health, and performance should be measured with many potential mutual dependencies among these variables (e.g. long questionnaires on comfort might negatively affect mood), and as time necessary to reach experimental condition defines flight sequence, test sequence had to be carefully designed and aligned with flight sequence. Figure 1 presents the test sequence for all experimental conditions in the 2 X 4 design in order to use the same time line for every participant.

In the first hour before the actual experiment, subjects were welcomed, got a snack, and got familiarized with the setting. Moreover, a last onsite screening with a "fit to fly" decision by a physician was done before boarding. During ascend and descend only control and manipulation check measures were done while all experimental outcome variables were measured at different (repeated times) during "steady state" of the exposure condition.

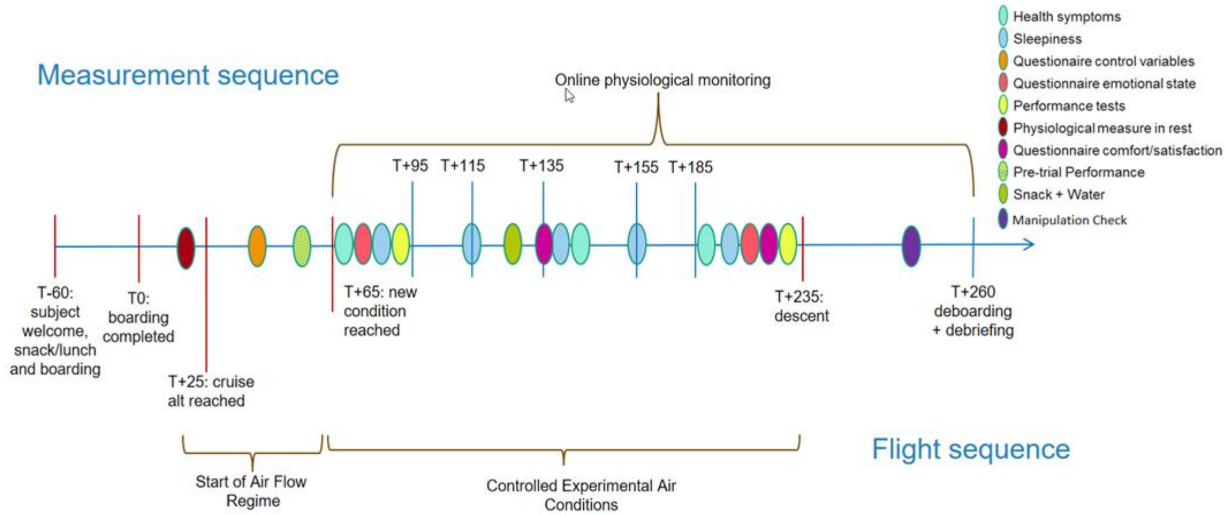

Figure 1: Test sequence aligned with the "flight" sequence of the ComAir main study design

D. Operationalizations & Measures

Comfort and wellbeing measures are considered as primary outcomes. They are operationalized by a) a wellbeing component (subjective wellbeing as emotional state and level of unpleasant feelings), and b) health status (subjective health symptoms assessed with visual analogue symptoms scales, level of sleepiness and fatigue, and heart rate variability). Comfort was assessed by five-point Likert scales containing 25 different aspects to be rated on their pleasantness and importance as well as one overall comfort rating and one rating for controllability. In addition, measures of air quality acceptability were added at the end of flight.

Cognitive performance was assessed as a secondary outcome and several potential control variables were considered as they can play an important role in how respondents will evaluate their comfort or wellbeing. These variables were a) sociodemographic questions; b) flight experience; c) health-related questions (general assessment of current health and of health at day of flight; smoking habits; and multiple chemical sensitivity); d) negative affectivity as person-related, 'stable' characteristic; e) proxemics and personal space; and f) general stress reactivity.

At the end of the exposure, during descend, participants had to fill-in a manipulation check questionnaire to assess how realistic the flight simulation was with regard to their usual flight experiences.

Environmental measures were taken throughout the session and at dedicated times in line with the psychological measures in the cabin. Air temperature, vertical stratification assessment, relative humidity, CO_2 and VOC were measured at dedicated spots in the cabin (see below).

Measures for the study were selected to be established, reliable and valid measures targeting different facets of the relevant constructs.

IV. First results from baseline exposure conditions

As the ComAir experimental sessions were conducted till the end of January 2020, only preliminary results are available yet. Therefore, some results from the baseline exposure, that is, half and fully booked sessions with a target CO_2 concentration of 1.200 ppm will be reported here. The aim is to show how the air regime translates into real environmental condition, whether this air regime already has an impact on a variety of comfort and wellbeing measures, and if the second factor in the study (occupancy) plays a (differential) role in these relations.

A. Sample

Overall, 143 persons participated in the three sessions denoting the baseline air regime; 73 in the half-booked condition (38 male, 35 female, mean age 43.16 years, SD = 16.6) and 70 in the fully booked condition (37 male, 33 female, mean age 43.23 years, SD = 16.2). Necessary sample size was reached and comparability of participants between the two conditions was given for a large number of additional variables (like e.g., education, occupational qualification, general health and related concepts, flight experience); that is, randomization was successful.

B. Environmental Measurements

Figure 2 shows a seat map of the cabin and the distribution of measurement locations. Environmental measurements of temperature in three heights (0.1, 0.6 and 1.1 m), relative humidity (1.1 m) and CO_2 (1.1 m) were constantly logged throughout the experiment. Additionally, samples for air quality and VOC assessment were drawn three times during the session (place 3D) and later analyzed.

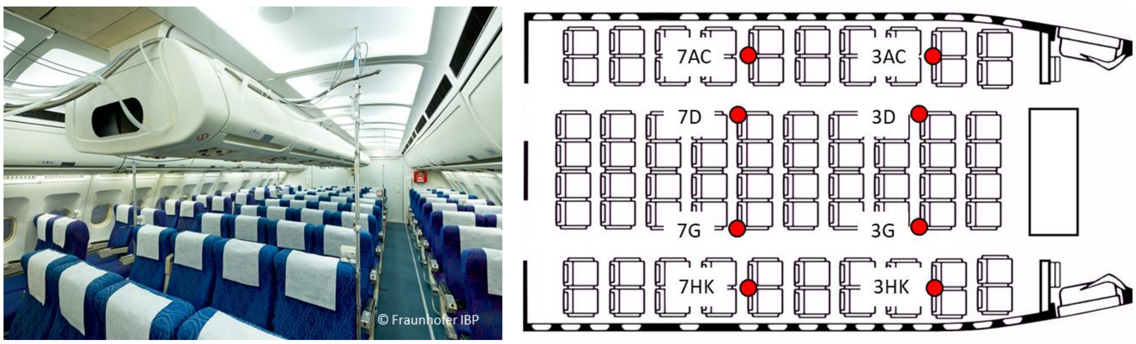

Figure 2: Cabin seat map and measurement locations

Overall, a good homogeneity of measurement data is found throughout the measurement location, thus only low spread. Especially CO_2 concentrations and humidity show to be very homogeneous. During data evaluation some sensors had to be excluded e.g. because it got obvious that CO_2 loggers were breathed upon or temperature sensors were touched by subjects. However, these are only few events and it is not expected that the overall result is impacted. The blue boxes in the background of the following figures 3 to 5 depict the span of average values in aircraft cabins reported in literature. These values have been systematically reviewed and summarized as part of the ComAir project.

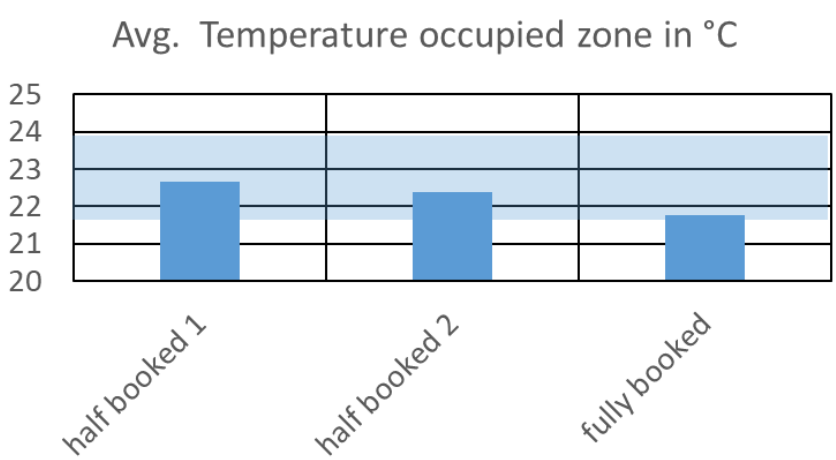

Figure 3: Average cabin air temperature during the exposure

Figure 3 shows the average air temperature during the baseline exposures. In order to avoid the impression of hot and stale air, the temperature was intentionally set to the lower limit of normal temperatures. In the fully occupied case, the lowest temperatures are encountered, probably due to the highest heat load density in the cabin resulting in the ventilation control to supply lower air temperatures.

The cabin ventilation system provides a dehumidifier in order to feed the mock-up with dry air. Through this, real cruise relative humidity can be replicated. Figure 4 shows the measured relative humidity in the cabin and proofs that it well aligns with data from real aircraft cabins as found in the literature.

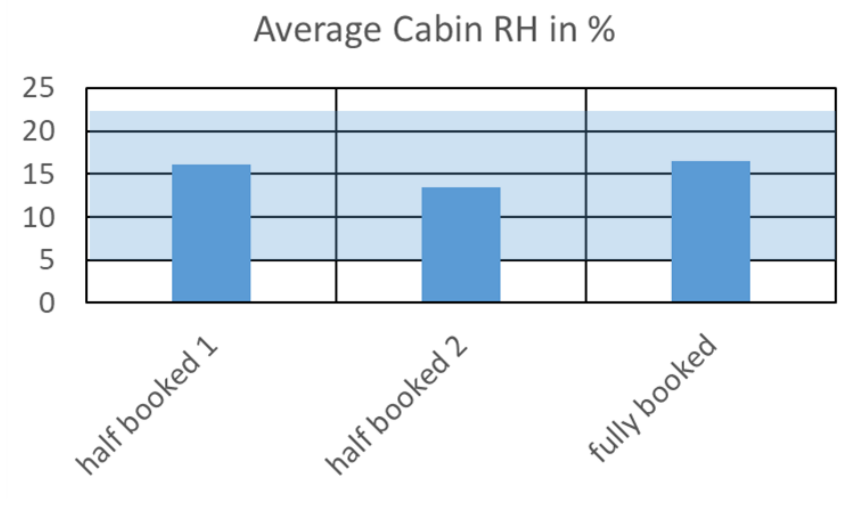

Figure 4: Average cabin relative humidity during the exposure

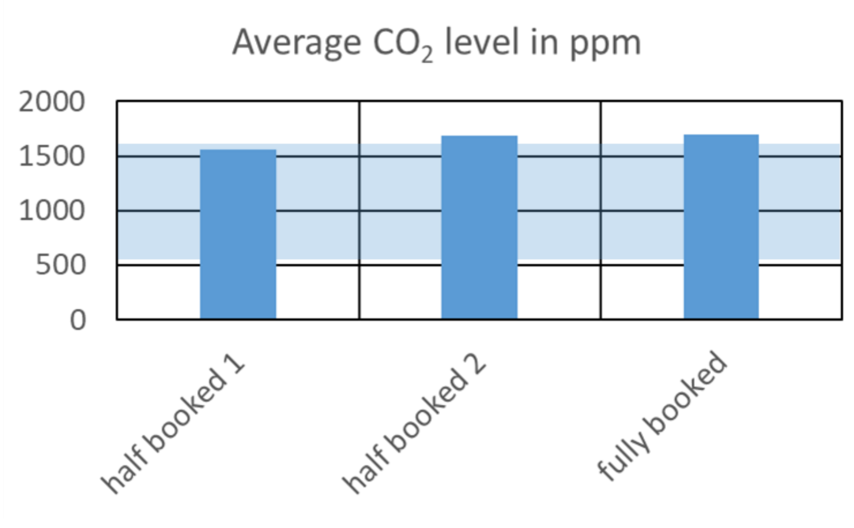

Figure 5: Average cabin CO_2 level during the exposure (pressure corrected)

Figure 5 shows the average cabin CO_2 level during the exposure. To pressure correct the raw data, the formula

$$c_{corrected} = c_{raw} \cdot \frac{1013\boldsymbol{h}Pa}{755\boldsymbol{h}Pa}$$

Thus, values shown correspond to a span of raw readings of 1159 to 1263 ppm and thus reflect the target concentration set out in Table 1. It is obvious that these concentrations are at the upper edge of concentrations reported in literature. However, it should be considered that the outside CO_2 concentration in Holzkirchen may be higher than at cruising altitude levels. Furthermore, ventilation was adapted to the number of passengers; thus from a ventilation point of view each experiment considers a full aircraft whereas field studies may encounter free seats in the aircraft.

First results for monitored human effluent VOCs show that these are as well within the range of reported quantities in the cabin. With values between 63-142 µg/m³ they are on the lower side of cabin values reported in literature.

C. Comfort, health and wellbeing

Subjects' ratings on comfort, health and wellbeing were analyzed using controlled analyses of variance with repeated measures and the occupancy factor as between measure. Overall, only few systematic, significant effects could be found in the baseline air ventilation regime. With regard to comfort, 9 specific aspects (e.g., air movement, air quality, space) and two overall ratings on comfort and controllability of the environment measured in the middle and end of the flight were analyzed. In general, the level of comfort/pleasantness was rated rather good (between 3 and 5 on a 5-point Likert scale), and although most ratings show a small decrease over time, there are no substantial significant main effects for repeated measures but four rather strong main effects (partial $\eta^2 \geq 0.06$) of the occupancy factor: Comfort with regard to privacy (half-booked: $EMM_{t1} = 4.20$, $EMM_{t2} = 4.04$; fully-booked: $EMM_{t1} = 2.67$, $EMM_{t2} = 2.59$; $F = 129.2$, $p < 0.000$); comfort with regard to personal space (half-booked: $EMM_{t1} = 3.68$, $EMM_{t2} = 3.65$; fully-booked: $EMM_{t1} = 2.80$, $EMM_{t2} = 2.75$; $F = 25.3$, $p < 0.000$); controllability of the environment (half-booked: $EMM_{t1} = 3.19$, $EMM_{t2} = 3.16$; fully-booked: $EMM_{t1} = 2.43$, $EMM_{t2} = 2.35$; $F = 29.4$, $p < 0.000$) and overall comfort (half-booked: $EMM_{t1} = 3.67$, $EMM_{t2} = 3.35$; fully-booked: $EMM_{t1} = 3.25$, $EMM_{t2} = 2.90$; $F = 8.5$, $p = 0.004$). Correlation analyses show that privacy and space are those aspects that are most closely related to the overall comfort rating (r=0.418/0.495 at t1 and r=0.456/0.511 at t2), showing that even in rather good environmental conditions (i.e. the baseline ventilation regime) proxemics, the occupancy of the cabin, dominate comfort perceptions. There were no differential effects for air quality ratings, i.e. participants in the half and fully booked conditions perceived it in the same way, and only small effects for comfort with regard to air movement and temperature that could be directly traced to the measured physical environment (see above).

With regard to health, visual analogue scales for 25 health symptoms were measured at the beginning, in the middle and at the end of the flight, psychological wellbeing in the beginning and at the end of flight as well as sleepiness that was measured five evenly spaced times throughout the flight. Changes in health symptoms were usually very low with change rates less than 2% of the scale ranges. Significant effects were only found for general symptoms like headache, circulatory problems etc. that decreased over time (main effect of repeated measures $F = 6.64$, $p = 0.002$) and for eye- and skin-related symptoms (interaction effect of time and occupancy $F = 5.73$, $p = 0.004$). Whereas participants in the fully booked condition show a ‚linear' increase in eyes- and skin-related symptoms, participants in the half-booked condition report a clear increase in these symptoms from the beginning to the middle of the flight followed by a decrease at the end. The single symptom with the 'strongest' increase over time (mean change +4 of 100) was a reported scratchy throat, the corresponding interaction effect for this symptom is presented in figure 6 (interaction times X occupancy: $F = 3.72$; $p = 0.027$).

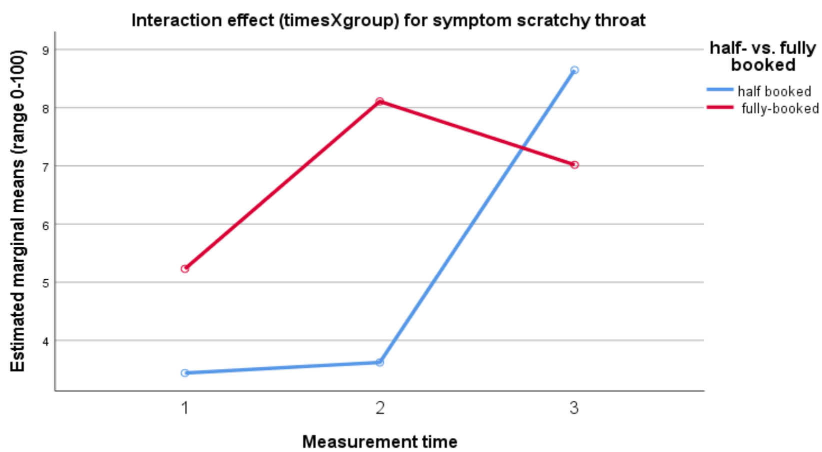

Figure 6: Interaction effect for single health symptom 'scratchy' throat

For all single and scaled symptoms that show an increase the most probable reason is the relatively low but typical relative humidity in the cabin.

Psychological wellbeing was neither impacted by the course of time in the cabin nor the occupancy, and only very small effects for sleepiness were found showing a curvilinear trend of decreasing and then increasing sleepiness over time. For all reported aspects a number of person-related control variables had a differential impact, e.g. negative affectivity influenced the reporting of symptoms as well as psychological wellbeing which stresses the importance of including the individual when researching the relationship between environment and comfort and wellbeing.

V. Conclusion

This paper presents the background and design of the ComAir study along with some preliminary results on environmental and human wellbeing aspects during a simulated four hour flight with a traditional air ventilation regime. Environmental results show that we succeeded to expose participants to conditions comparable to real flights. Against this background, participants perceived comfort in different aspects medium to good and this overall trend aligns nicely with the environmental data that show rather normal to good indoor values without strong deviations.

There were only two specific comfort aspects where differences could be directly tracked to environmental conditions – the comfort perceptions regarding temperature and air movement are significantly, (but with only a small effect size) lower in the fully booked condition than in the half booked condition. Specifically the second aspect might be a result of the ventilation regime, that is, the highest total airflow rate in the cabin in the fully booked condition.

Nevertheless, the strongest effects for comfort perceptions relate to the social environment, i.e. not environmental conditions but the occupancy factor itself: As expected and in line with research in open space offices, satisfaction with privacy and space is notably lower in the fully booked condition than in the half-booked condition.

The overall good impressions from the comfort rating can also be seen for the health symptoms which are in general rather low and do not change much during the flight. General symptoms decrease over time, which might be an effect of the calmness of just sitting in the cabin under relatively good indoor conditions. Psychological wellbeing seems to be completely unaffected by the experimental and environmental conditions. The rather small effects for sleepiness with small nonsignificant increases are most probably due to the situation of four hour sitting in a cabin with not too much to do.

Taken together, for the traditional air regime only a few and small effects on comfort and wellbeing can be detected but of these some plausible correlations with environmental conditions might exist. Next steps are the analyses of all experimental conditions, the evaluation of passengers' reactions to cabin conditions with increased recirculated air rates compared to the baseline situation to better understand the effect of CO_2, VOCs and air quality in general on human comfort perception, wellbeing and health.

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