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Effects of increased recirculation air rate and aircraft cabin occupancy on passengers' health and well-being – Results from a randomized controlled trial

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A R T I C L E I N F O

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Health symptoms
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A B S T R A C T

Background: Aircraft cabins are special environments. Passengers sit in close proximity in a space with low pressure that they cannot leave. The cabin is ventilated with a mixture of outside and recirculated air. The volume of outside air impacts the carbon footprint of flying. Higher recirculation air rates could be considered to save energy and divert less kerosene from producing thrust.

Objectives: To investigate whether higher recirculation air rates in aircraft cabins negatively affect passengers' health and well-being and if occupancy plays a role in this.

Methods: In a 2 (occupancy: full and half-occupied) X 4 (ventilation regime) factorial design with stratified randomization, participants were exposed in an aircraft segment in a low-pressure tube during a 4-h simulated flight. Ventilation regimes consisted of increasing proportions of recirculated air up to a maximum CO_2 concentration of 4200 ppm. Participants rated comfort, health symptoms, and sleepiness multiple times. Heart rate (variability), as stress marker, was measured continuously.

Results: 559 persons representative of flight passengers regarding age (M = 42.7, SD = 15.9) and sex (283 men) participated. ANCOVA results showed hardly any effect of both factors on self-reported health symptoms, strong main effects of occupancy on comfort measures, and interaction effects for sleepiness and physiological stress parameters: Participants in the half-occupied cabin hardly reacted to increased recirculation air rates and show overall more favorable responses. Participants in the fully occupied cabin reported higher sleepiness and had stress reactions when the recirculation air rate was high.

Discussion: This large-scale RCT shows the importance of occupancy, a previously neglected factor in indoor air research. The proximity of other people seems to increase stress and exacerbate reactions to air quality. Further studies on causal pathways are needed to determine if recirculation air rates can be increased to reduce the carbon footprint of flying without detrimental effects on passengers.

1. Introduction

Commercial flights contribute to environmental impacts and climate change. The development of more environmentally friendly aircraft requires many initiatives to reduce fuel usage. An essential contributor to fuel use is the system to control the environment in the cabin where the outdoor air is taken from the jet engine; this air cannot be used for thrust. One way to reduce this loss is to increase the rate of recirculation. For example, Hunt et al. (1995) estimated that for a Boeing 767, the use of pure outside air would result in a total impact of 1.6% fuel burn, whereas a mixture of 50% outside and 50% recirculated air reduces the impact to 0.8%. With this, it can be assumed that each 10% reduction of outside air results in 0.16% less fuel burn. In a more recent study, Zavaglio et al. (2019) even estimate the impact of the environmental control system up to 5% of fuel burn, and that an adaptive reduction of outside air might save up to 2% fuel consumption (see supplement part A for an estimate in this study). However, increased recirculation air rates may impair crew and passengers' comfort, health, and safety. The

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present study was performed within the European Union's Clean Sky initiative to investigate whether this would be the case.

Aside from the special pandemic situation, the number of people traveling by commercial aircraft has increased in recent years. Aircraft cabins present indoor environments with distinctive features. They are characterized by high occupant density, inability to leave the environment, low relative humidity, need for pressurization, and pollutants whose origin are predominantly passengers and their activities (Chen et al., 2021). All of this can produce adverse 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 (e.g., Cincinelli and Martellini, 2017; National Research Council, 2002; Zubair et al., 2014). Increasing recirculation air rates could exacerbate these effects by increasing the amount of air pollutants because less outside air is available for dilution.

One effect of increasing recirculation rates is increased carbon dioxide (CO_2) levels. CO_2 has been used as an easy-to-measure marker of air quality. However, indoor air quality (IAQ) is determined by many different compounds, and the evidence for effects of CO_2 itself on health and well-being is conflicting (Fisk et al., 2019; Jacobson et al., 2019; Lowther et al., 2021) below lethal concentrations of 8–10 vol.-% in the air. For example, maximum workplace concentration of CO_2 is 5.000 ppm (0.5 vol.-%) (Deutsche Forschungsgemeinschaft, 2021), but some studies have already observed effects on cognitive performance at 1000 ppm CO_2 compared to lower levels (Allen et al., 2016, 2019; Satish et al., 2012) while others do not see any health and cognitive effects at exposure levels as high as 20,000 ppm CO_2 (Maniscalco et al., 2021). Along with subjective health symptoms and cognitive performance, some studies of IAQ considered physiological measures such as heart rate and heart rate variability (HRV) as indicators of stress and arousal (e.g., Kajtár and Herczeg, 2012; Zhang et al., 2017). A recent study explored the HRV on commercial airline pilots and their performance on flight maneuvers (Cao et al., 2019). Results showed that lower HRV was associated with pilot performance, however, independent of the effects of CO_2 exposure.

Health effects are part of the broader concepts of well-being and comfort. Subjective well-being includes an affective and a cognitive component The cognitive component encompasses satisfaction with air quality and other environmental conditions during a flight. Positive affect of the affective component includes feelings such as serenity, relaxation, and, among others, comfort, pointing out the association of well-being and comfort as a short-term well-being phenomenon. Recent studies show the importance to focus on the complex interaction of these individual perceptions with a number of other person- and environment-related aspects (e.g., Ahmadpour et al., 2016; Liu et al., 2017). In aircraft cabins, proximity of other people is a dominant environmental factor worth addressing. The term proxemics (Hall, 1966) refers to the perceived relationship between the social and physical distance in human interactions (Ahmadpour et al., 2014). Its most important aspects 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 (Hall, 1966). An online survey study (Lewis et al., 2017) showed that invasion of personal space, caused by physical factors (e.g., physical contact with humans) and sensory factors such as noise, smells, or unwanted eye contact, can negatively impact passenger comfort. In addition, Ahmadpour et al. (2014) found in a qualitative study with 158 participants that proxemics and desire for privacy were among the most important themes related to comfort in the cabin interior reported by passengers.

Research on aircraft cabin air quality, comfort, and well-being parameters of passengers is still rather scarce. Strøm-Tejsen et al. (2007) investigated a trade-off between outdoor airflow rate and cabin air humidity. In 7-h flight simulations with four groups of 16–18 participants, the authors found that increasing humidity in the aircraft cabin from 7 to 28% by reducing outside airflow from 9.4 to 1.4 l/s per person did not reduce the intensity of health symptoms but intensified complaints of headache, dizziness, and claustrophobia, due to the increased level of contaminants. Follow-up research that used purification units in the recirculated air showed positive (Strøm-Tejsen et al., 2008) but also mixed effects (Sun et al., 2008) on well-being for different devices. Within the Ideal Cabin Environment (Ideal Cabin Environment, 2017) Research Consortium Grün et al. (2008) investigated the effect of temperature, relative humidity, noise, and environmental pressure parameters on perceived comfort. Their study included 17 simulations of 7-h flights with forty subjects in each flight and pre-post comfort measures. Interrelations of thermal comfort, temperature, and noise were found. Additionally, low pressure affected thermal comfort when the background noise was lower.

To sum up, although physical measurement of air quality in aircraft cabins has been the focus of numerous studies (e.g., Crump et al., 2011; Guan et al., 2014a; b, Guan et al., 2015; Schuchardt et al., 2017; Chen et al., 2021) and there are a lot of studies researching health effects of IAQ in other settings (e.g. homes: Vardoulakis et al., 2020; schools: Baloch et al., 2020; work place: Spinazzè et al., 2020), the impact of air quality in terms of CO_2 and VOCs (as the two parameters most affected by increased recirculation air rates) on health, well-being, and comfort in aircrafts has been less often researched. Only few studies did this in a controlled way; however, with small sample sizes and cross-over designs. Studies with large-scale experimental (RCT) approaches concerning CO_2 and VOCs are missing to the best of our knowledge. In addition, as air quality might only be one (small) aspect of well-being perceptions (see for a ranking of comfort "driver" Bouwens et al., 2018), another previously neglected aspect is personal space in the sense of proxemics (Hall, 1966). Its psychological dimension has not been researched with experimental approaches in the context of flying so far. The present work attempts to address these gaps.

1.1. *Objective and hypotheses*

The overall aim is to determine if outside air rates in aircrafts can be reduced (with the consequence of increasing CO_2 and VOCs) without a negative impact on passengers' comfort and health and whether these effects depend on the number of people in the cabin. If a reduction without negative impact on passengers is possible, this would help to lower fuel use and reduce emissions from air traffic. Consequently, we examined the following hypotheses.

- Reduced air quality in terms of reduced outside air rate leads to reduced comfort and well-being in terms of health symptoms and stress reactions of passengers in aircraft cabins under flight conditions.
- Level of comfort and well-being develops linear with air quality in terms of outside air rate.
- Level of comfort and well-being is lower in fully occupied aircraft cabins than in half-occupied cabins, even if the ventilation rates per person are unchanged.
- Proximity of other passengers (occupancy) moderates the effects of air quality on comfort and well-being in such a way that even with high outside air rates (good air quality) comfort and well-being is lower in a fully occupied cabin than in a half-occupied cabin.

2. Materials and methods

2.1. *Study design*

To test the research questions, we conducted a study simulating a medium-length flight following a 2 (occupancy) X 4 (air ventilation regime) full-factorial, single-blinded, randomized controlled trial (RCT) design with stratification for age and sex. Occupancy denotes the number of people in an aircraft cabin (half- vs. fully occupied cabin). The four ventilation regime levels represent different outdoor air supply rates (and recirculation rates). The total aircraft cabin flow remained unchanged matching aviation standard requirements (ASHRAE Standard 161, 2007) as follows: baseline with the aircraft airflow regimes per person to match typical levels of CO_2 measured on aircraft, regulatory ASHRAE 161 requirement (standard), ASHRAE 161 half (half of the recommended flow), and a recirculation regime with airflow to match CO_2 concentration close to the regulatory limit in the aircraft cabin (see Exposure section). All four air ventilation regime sessions were repeated thrice: once with a fully occupied cabin and twice with a half-occupied cabin (see Sample section). Age/sex strata from the Airport Travel Survey (Flughafenverband, 2015, 2018) were used for stratified randomization of participants to reach a sample composition in each experimental condition that is representative of flight passengers. Randomization was done with the Etcetera module from the Winpepi program group (version 11.65, Abramson, 2011). The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee at the Faculty of Medicine, Ludwig-Maximilians-University, Munich (ID: 19–256). Written informed consent was obtained from all participants.

2.2. Exposure

All experimental sessions were performed during simulated four and a half hour flights carried out between November and December 2019 in the Fraunhofer Flight Test Facility (FTF) in Holzkirchen (Germany) that consists of a low-pressure vessel with the inserted front part of a former in-service wide-body airplane cabin (Airbus A310) including cockpit, galley, and seating for up to 80 passengers. Cabin pressure was maintained at 755 hPa, typical of cruising altitude corresponding to regulatory limit of 8000 feet pressure altitude, target cabin temperature was set at 23 °C.

With a constant total flow rate of 9.4 L/s per person for all experimental conditions matching the aviation standard (ASHRAE Standard 161, 2007), the following target outside and recirculation air rates were aimed for with CO_2 levels on aircrafts from typically found mean levels (about 1200 ppm, Chen et al., 2021) to levels lower than but close to the regulatory limit (5000 ppm, e.g., FAA, 2019; EASA, 2019):

- Baseline condition, target CO_2 of 1200 ppm (termed 'Baseline'): outside air rate of 5.2 l/s/person, recirculation air rate of 4.2 l/s/person.
- ASHRAE 161 condition, target CO_2 of 1650 ppm (termed 'ASHRAE'): outside air rate of 3.5 l/s/person, recirculation air rate of 5.9 l/s/person.
- ASHRAE 161-half condition, target CO_2 of 2750 ppm (termed 'ASHRAE half'): outside air rate of 1.8 l/s/person, recirculation air rate of 7.6 l/s/passenger.
- Max. CO_2 condition, target CO_2 of 4200 ppm (higher CO_2 not possible due to recirculation air cooling capacity limitation) (termed 'Max. CO_2'): outside air rate of 1.1 l/s/person, recirculation air rate of 8.3 l/s/passenger.

Neither CO_2 nor air pollutants were dosed into the cabin but built up "naturally" from the sources in the cabin, mainly subjects, their activity, and belongings. To avoid too large differences in VOCs between experimental conditions, participants were asked to avoid scented cosmetics or perfumes on the test day and not to bring their own food and drinks. Low emitting food, such as water and pretzels, was provided once in the middle of the flight, and VOCs in the cabin were constantly monitored. Technical details can be found in Norrefeldt et al. (2021). Table 1 summarizes the exposure conditions resulting from the different air ventilation regimes and occupancies. In line with other measurements of VOCs in indoor air (Chen et al., 2021; Tang et al., 2016), the largest amount of VOCs in the experimental conditions came from the

Table 1
Summary of environmental parameters in experimental conditions.

	Baseline				ASHRAE				ASHRAE half				Max. CO2			
	Half-occupied N = 73		Fully occupied N = 70		Half-occupied N = 74		Fully occupied N = 71		Half-occupied N = 71		Fully occupied N = 62		Half-occupied N = 71		Fully occupied N = 67	
	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max	Entire Exposure	Max
Temperature in °C	22.6	22.9	21.8	22.2	23.2	24.2	23.4	23.6	23.4	23.8	23.3	23.5	23.6	23.8	25.4	25.9
Relative Humidity in %	15	16	17	17	17	18	19	20	20	25	24	26	22	27	30	34
CO_2 in ppm	1619	1746	1695	1721	2000	2094	2269	2341	2778	3105	3219	3378	3386	4076	4150	4520
TVOC in µg/m^3; thereof 7 VOCs with highest amount across all conditions	112	142	82	100	278	405	147	173	358	411	909	1682	588	1103	391	412
…																
…ethanol (µg/m^3)	31	72	26	46	149	260	35	46	95	171	675	1330	233	359	139	172
…acetone (µg/m^3)	22	27	14	15	24	26	28	30	38	41	50	53	58	70	50	53
…2-propanol (µg/m^3)	3	4	1	1	5	7	2	3	20	30	49	124	82	350	20	26
…acetic acid (µg/m^3)	17	27	12	15	17	24	26	37	23	32	32	45	32	54	41	43
…ethylene glycol (µg/m^3)	10	18	43	48	18	26	13	17	47	57	29	38	45	69	43	48
…isoprene (µg/m^3)	12	19	11	12	16	19	14	17	23	35	25	31	29	38	38	40
…1,2-propandiol (µg/m^3)	14	23	6	8	20	30	12	13	32	36	19	24	27	33	24	25
Particles per ml	1091	1366	829	845	926	1077	1077	1095	990	1030	988	1058	1098	1221	1496	1512
Fresh air per person incl. Crew in l/s	5.2		5.2		3.5		3.5		1.9		1.9		1.15		1.1	
Fresh air per person excl. Crew in l/s	5.7		5.5		3.85		3.7		2.1		1.9		1.25		1.2	
Total airflow in m^3/h	1386		2482		1401		2260		1372		2167		1356		2228	

Note: N=Number of participants per condition; entire exposure measures are averaged data, max. values represent peaks measured during the exposure, for details see Norrefeldt et al. (2021); VOCs were measured by gas chromatography – mass spectrometry (GC-MS, Shimadzu QP2010 SE) as well as carbonyl-compounds (aldehydes, ketones) by high performance liquid chromatography with diode array detector (HPLC-DAD, Agilent 1260 Infinity) after pumped sampling on Tenax TA ® adsorbent tubes (ISO 16000-6) and DNPH cartridges (ISO 16000-3), respectively.

participants either as bioeffluents (ethanol, acetone, isoprene, acetic acid) or as compounds probably brought in via personal belongings (ethylene glycol, propandiol, as part of antifreeze agent in windscreen wiper fluid/experimental sessions took place in winter). 2-propanol can have different sources (like antifreeze, cosmetics or household cleaners). Since the largest amounts were found in the experimental condition in which the toilet in the cabin had to be cleaned because a participant had vomited (see supplement part B), we assume that the latter is probably the main source.

2.3. *Sample: size, criteria, recruitment, and screening*

An a priori sample size estimation with G*Power 3.1 (Faul et al., 2009) showed a minimum required sample size of N = 551 participants (based on ANCOVA; alpha-error of 5%, power of .85; small to medium-sized effects (f = 0.15; η^2 = 0.022) to be detected; 10–20 covariates). With a predicted dropout quote of about 10% during pre-screening, 600 participants were targeted. This meant about 75 participants for each fully-occupied condition and about 35–40 for each half-occupied condition. Participants were recruited via an agency for background actors (extras) to reach this sample size in the respective age and sex strata. Inclusion criteria were healthy adults willing and able to give informed consent. Exclusion criteria were persons with chronic respiratory and heart conditions as well as severe anemia, potential outliers in comfort and well-being measures (e.g., people who cannot sit without pain for 3–4 h), unrepresentative people (people who have not flown so far), people that might cause problems during experiments (e.g., people who have fear of flying or claustrophobia, people under the influence of alcohol or drugs, aggressive), and persons potentially at risk (e.g., with a deep vein/pelvic thrombosis in the past or pregnant women).

A three-step screening procedure was used to ensure that these criteria were met. First, potential participants received a pre-screening self-check together with the study information. Respondents needed to answer several easy performance-based questions intended to identify risk groups, such as “I have troubles breathing when climbing two flights of stairs”, which screens out people with chronic respiratory and heart conditions. A few days before the experiment participants were reminded to call in sick if they had a current cold, cough, sneezing, or known infectious diseases. This was also checked during the onsite screening right before the trials: as second screening part, participants completed a short set of questions providing information on severe surgery, cardiac infarction, or pneumothorax in the past six months, as well as on ongoing cold, sinusitis, etc. As a third step, participants were individually checked by onsite physicians, who excluded unfit participants as well as participants who were aggressive, visibly intoxicated, or showed other behavioral problems. Twenty-four participants called in sick on the day of the trial; the onsite physicians screened out 6. In addition, one person aborted during the trial and left the FTF via pressure lock (see CONSORT scheme in Supplement part B). Overall, 559 subjects participated, and the necessary sample size was reached.

2.4. *Self-report measures*

Comfort was measured with different subscales adapted from the IEQ questionnaire (Veitch et al., 2007; Newsham et al., 2008) and the ICE project (2017). Participants had to rate several environmental factors using five-point Likert scales indicating how pleasant/comfortable the factors were (1 = not pleasant at all, 5 = very pleasant): Air quality subscale contained four items (e.g., fresh air, humidity) and showed good internal consistency (Cronbach’s α = 0.801); temperature contained four items on temperature at different body parts (e.g., temperature at feet, Cronbach’s α = 0.890). Space subscale contained two items on seat width and legroom with a satisfying internal consistency of Cronbach’s α = 0.755. Satisfaction with privacy subscale contained four items (e.g., distance to others) with a very good internal consistency of Cronbach’s α = 0.908. In addition to these specific aspects, one single item on general comfort experience was used with the same five-point Likert scale. These comfort ratings were measured twice, in the middle and at the end of the cruising phase of the simulated flight.

Health symptoms were assessed three times (beginning, middle, and end of exposure) using a list of 22 symptoms that had to be rated regarding their intensity on visual analogue scales (0–100) (adapted from Schnuch et al., 2010, and Herbig et al., 2018). Symptoms comprised general (e.g., headache; 6 items, Cronbach’s α = 0.729), respiratory (e.g., dry cough; 4 items, Cronbach’s α = 0.608), skin-/eye-related (e.g., itchiness; 5 items, Cronbach’s α = 0.785), and throat-/nose-related (e.g., scratchy throat; 7 items Cronbach’s α = 0.660) and were used as sum scales.

As a relatively fast developing state, sleepiness was measured five times equally distributed during the exposure with the three-factor binary Yoshitake measure (Yoshitake, 1973, 1978). It consists of a list of statements where participants have to check whether they agree or not and is scaled as percentage of answers agreeing with the items; thus, it has a range of 0–100 with higher values denoting more sleepiness. The three factors are drowsiness and dullness (e.g., I would like to lay down, 10 items), difficulty of concentration (e.g., I can’t think clearly, 10 items), and projection of physical impairment (e.g., My shoulders are tensed up, 10 items), whereby the first factor captures genuine sleepiness the other two are more related to fatigue.

Control variables measured before exposure during ascend consisted of single-item sociodemographic and health-related aspects (age, sex, education, average number of flights p.a., BMI, and smoking) and person-related variables likely to impact health, well-being, and current state variables. As person-related control variables, we measured *general health* assessed with the Short Form-8 (SF-8) Health Survey (abbreviated SF-36 Health Survey; Ware et al., 2001; German version Ellert et al., 2005; Cronbach’s α = 0.801). Self-reported *multiple chemical sensitivity* (sMCS) was assessed with a five-point Likert scale (1 = not at all, 5 = very much) developed by Kiesswetter and colleagues (1997, 1999), which contains eight items on adverse bodily reactions to offensive smells in the environment (e.g., “I feel dizzy when I perceive the strong odor of varnish or smoke”; Cronbach’s α = 0.906). *Negative affectivity* was assessed via a short version of the negative affect scale of the PANAS by Watson et al. (1988) with five adjectives on different feelings and emotions (Cronbach’s α = 0.750). As a final person-related characteristic concerning the occupancy factor *proximity preferences* were assessed using a projective technique called interaction distance image (Lewis et al., 2017). Respondents need to note the number on a picture which corresponds to their preferred comfortable conversation distance from a close friend and from a stranger, with higher numbers showing higher distance. As current state control variables, sleep quality in the night before the test was controlled using two questions from a representative German cohort study (Robert-Koch-Institut, 2008), and health at the day of the test was assessed through a standardized one-item measure reported by McDowell (2010).

2.5. *Physiological measures*

As an easy to sample, robust yet sensitive enough marker of autonomous activation, HR and HRV of the participants were monitored. These measures of the physiological stress response of the participants have already been used in similar research contexts as ours (e.g., Cao et al., 2019). HR and HRV were measured with the Firstbeat Bodyguard 2 device (Firstbeat Technologies Ltd.). It is a lightweight R-R interval recording device that is attached directly to the skin with two chest electrodes. Precision is 1 ms (with a sampling frequency of 1000 Hz). A white paper is available (Parak and Korhonen, 2013).

Guidelines on using HRV in occupational medicine (Sammito et al., 2021) recommend a measurement in rest of at least 5 min to be able to reliably interpret results. As this problem is aggravated in group-based analyses, a dedicated 7 min time span before the air quality exposure started was announced where people should sit relaxed but without too much movement in their seat. The HR and HRV data from this timeframe were used as individual rest measure to control the monitoring data during exposure (see statistical analyses).

The following parameters are used in the analyses: HR is measured by the number of heart contractions (beats) per minute (bpm). As HRV parameters, the time-domain measures RMSSD and SDNN are reported, and the frequency domain parameter of LF/HF ratio. RMSSD (root mean square of successive R-R intervals) is a parameter of short-term variability, reacting fast to a situation where the autonomous nervous system has to adapt. It is assumed to be a marker for decreased vagal activity and is used to look at the parasympathetic influence. SDNN in ms is the standard deviation of all normal-to-normal intervals and is used as a frequency-independent indicator of the overall variability. It is assumed to show increased sympathetic activity. Usually, a reduced SDNN is interpreted as a longer-term parameter of stress. Low Frequency (LF)/High Frequency (HF) ratio is an index of the interaction between sympathetic and vagal activity whereby HF is a marker of the parasympathetic tone, and LF is possibly correlated to sympathetic tone or autonomic balance; that is, vagal and sympathetic influences are involved, but the part of sympathetic activity dominates. A higher LF/HF ratio is indicative of stress or sympathetic activity.

The last parameter – recovery time (in minutes) – is a summary measure (Firstbeat Technologies Ltd, 2014). It defines recovery as times when parasympathetic activity dominates the autonomous nervous system and sympathetic activation is low. The method detects recovery following a fixed selection procedure of data segments. Recovery time is used as a counterpart of the HR and HRV stress measures.

2.6. Procedure

All twelve experimental sessions (4 fully occupied, 8 half-occupied) took place on individual workdays in November and December 2019. Upon arrival at the flight test facility (about 10:00 a.m. on each test day), participants were checked in, received the printed informed consent forms and the second screening questionnaire. They were cabled for HRV monitoring and checked by the physicians, as described above. During waiting times, a small snack and non-carbonated non-alcoholic drinks were served. When everybody was ready, a safety instruction for the low-pressure vessel was given, and the experimenters performed a question and answering session for informed consent. Only after giving their written consent could participants board the aircraft. At about 11:00 a.m., the simulated flight began.

During the first approx. 25 min simulating ascend when the pressure in the FTF was decreasing to 755 hPa, there were no interventions to ventilation in the cabin, so all groups experienced the same conditions independently of the planned experimental condition. This time was used for the physiological measurement in rest. When flight altitude was reached, the targeted ventilation regime was set, and questionnaires on control variables were administered. The first questionnaire battery with health and well-being outcome variables was distributed when the targeted regime was reached (about 65 min into the flight). In the middle of the flight (at about 140 min), participants had to answer a second battery with comfort and health outcomes. A third battery was done at the end of the cruising phase, including comfort, health, and well-being measures again. Five times at equal intervals during the flight, participants reported their sleepiness. The cabin was depressurized at about 235 min into the flight, so the actual flight time at cruising altitude pressure was about 215 min. During descent, participants filled in a short manipulation check on the realism of the flight. After deboarding, heart rate monitors were removed and collected, and participants were debriefed and seen off. Fig. 1 shows the test sequence. The cognitive performance part in light grey contained an information processing speed test not reported here.

2.7. Statistical analyses

As the half-occupied conditions contained two experimental sessions for each air ventilation regime, comparability between sessions within each ventilation regime was checked via t-tests for independent groups. No systematic differences were found, and sessions were used as one group. To test the individual and combined effects of air ventilation

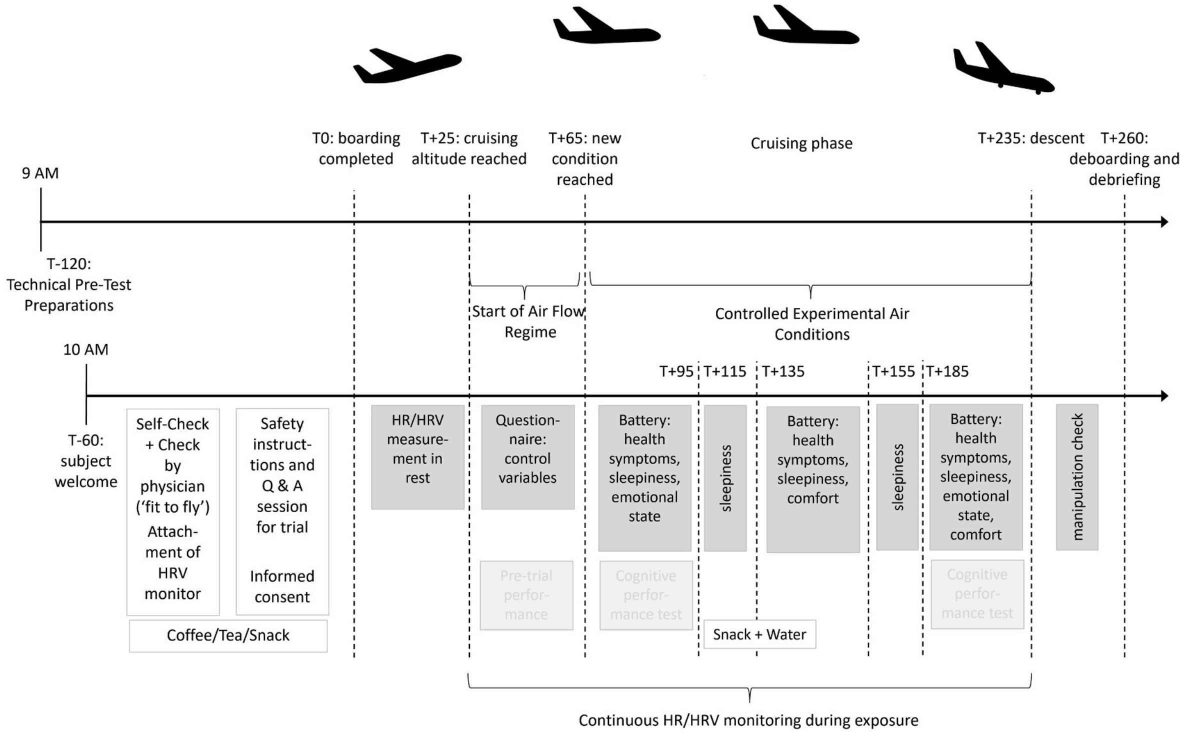

Fig. 1. Test and measurement sequence in simulated flight.

regime and occupancy on comfort and well-being in the 2 × 4 experimental design, analyses of (co)variance with repeated measures were carried out using IBM SPSS (Version 26.0). The statistical significance level was fixed at $p < .05$ (2-tailed). Effect sizes are reported as partial η^2 according to Ellis (2010) based on Cohen (1992). Posthoc comparisons of factor levels of air ventilation regime were conservatively Bonferroni adjusted for multiple testing, simple main effects within the factor levels of occupancy were done to describe potential interaction effects between the factors. As repeated measures ANCOVA require complete data sets, imputations were done on an individual basis; that is, no multiple imputation procedure was employed but missing data was added based on individual sequences following two rationales: First, only data for variables with more than two measurement times were imputed as otherwise no trend could be seen. Second, only those values were filled-in where preceding and subsequent values were valid or where a clear pattern (e.g., only yes in all other measures) was discernible. This resulted in 0.47% imputed data for the Yoshitaki sleepiness scales (392 out of 83,850 data points) and in 0.20% imputed data for self-reported health symptoms (83 out of 41,925 data points).

Preparation of physiological HR and HRV data for analyses included separation of measurements in rest and measurements during exposure, artifact correction, exclusion of overall nine participants with invalid measures (too many artifacts even after correction and exposure measure shorter than 30 min due to loosened electrodes) from analyses, and logarithmisation of time-domain HRV parameters for normalization (see Shaffer and Ginsberg, 2017). To account for the individual baselines, for all HR and HRV parameters and recovery time, rest measures were partialed out of exposure measures, and residuals were used for the analyses of variance.

As large-scale RCT might include high heterogeneity of subsamples, all analyses were controlled for several person-related aspects with potential relevance to the respective outcomes. For self-reported comfort, health symptoms and sleepiness, these were age, sex, BMI, smoking, sleep quality before exposure, health status, and multiple chemical sensitivity. For HR and HRV, age, sex, BMI, smoking, and length of measurement for time-domain HRV parameters were controlled. To ensure against overfitting, all crude models were also tested and are reported in the supplementary file part D.

3. Results

3.1. Sample characteristics and randomization check

In total, 283 males and 276 females (N = 559) participated, resulting in 50.6% men and 49.4% women with an overall mean age of 42.68 years (SD = 15.85; range: 18–79 years). 56.2% of participants achieved general qualification for university entrance/A level, 0.5% left school without graduation. The subjects flew 5.3 times per year on average (SD = 18.3; range: 0–260). BMI (M = 24.91; SD = 4.83) and general health (SF-8: M = 15.13; SD = 4.36) were in the normal range. To ensure that the samples in the different experimental conditions are comparable for all types of potentially relevant socio-demographic and control variables – that is, to ensure that randomization was successful – statistical comparisons via crosstabs or ANOVA were conducted (Table 2). All eight experimental groups were comparable except for smoking, multiple chemical sensitivity, and sleep quality the night before the test. Comparisons between single experimental groups show no systematic pattern, although group ASHRAE half, half-occupied cabin seems to be the driver behind the differences (highest multiple chemical sensitivity, worst sleep quality night before test, high proportion of smokers compared to non-smokers); these variables were controlled for in the main analyses.

Table 2
Sample characteristics and randomization check.

	Baseline; half-occupied (a)	ASHRAE; half-occupied (b)	ASHRAE half; half-occupied (c)	Max. CO_2; half-occupied (d)	Baseline; fully occupied (e)	ASHRAE; fully ocupied (f)	ASHRAE half; fully occupied (g)	Max. CO_2; fully occupied (h)	Overall difference: p-value
Male	38	39	34	33	37	33	32	37	.957
Female	35	35	37	38	33	38	30	30	
Age	43.16 ± 16.57	44.42 ± 16.31	43.08 ± 15.64	41.76 ± 15.60	43.30 ± 16.18	41.34 ± 15.36	41.21 ± 16.72	42.90 ± 14.84	.935
Body Mass Index	25.12 ± 4.90	24.14 ± 4.48	24.32 ± 3.75	24.45 ± 4.60	25.56 ± 6.36	25.12 ± 4.91	24.75 ± 3.91	25.88 ± 5.15	.336
Never smoked	44 $^{c\,e\,f}$	37	24 $^{a\,g\,h}$	31	28 $^{a\,g\,h}$	29 ^{a}	36 $^{c\,e}$	38 $^{c\,e}$	.018*
Do not smoke anymore	18	15	27	21	19	26	14	17	
Smoke occasionally	7	15	14	10	11	9	8	3	
Smoke regularly	4	7	6	9	12	7	4	9	
General health assessment [range 8–41]	14.60 ± 4.20	15.05 ± 4.25	15.49 ± 4.15	15.91 ± 4.64	15.14 ± 4.67	14.64 ± 3.95	15.07 ± 4.39	15.11 ± 4.72	.700
Proximity Preferences (Stranger) [range 1–4]	2.29 ± 0.59	2.31 ± 0.62	2.41 ± 0.62	2.36 ± 0.48	2.26 ± 0.61	2.31 ± 0.67	2.47 ± 0.65 ^{h}	2.23 ± 0.58 ^{g}	.391
Multiple Chemical Sensitivity [range 0–32]	4.44 ± 5.26 ^{c}	7.23 ± 6.15	8.04 ± 7.19 ^{a}	5.89 ± 5.70	5.16 ± 6.18	5.24 ± 6.09	5.76 ± 5.81	7.48 ± 6.62	.004**
Negative Affectivity [range 1–5]	1.30 ± 0.41	1.36 ± 0.47	1.38 ± 0.48	1.39 ± 0.42	1.32 ± 0.38	1.32 ± 0.43	1.46 ± 0.53	1.34 ± 0.40	.465
Average number of flights p.a.	6.67 ± 24.01	5.68 ± 10.48	8.91 ± 35.49	5.55 ± 18.22	3.50 ± 6.15	4.17 ± 9.41	2.79 ± 3.20	4.94 ± 15.48	.625
Sleep quality night before test [range 1–4]	2.99 ± 0.63 ^{c}	2.69 ± 0.79	2.34 ± 0.83 $^{a\,d\,e\,f\,g\,h}$	2.83 ± 0.79 ^{c}	3.00 ± 0.61 ^{c}	2.92 ± 0.67 ^{c}	3.00 ± 0.65 ^{c}	3.03 ± 0.63 ^{c}	.000***
Health on day of flight [range 1–5]	4.14 ± 0.77	4.12 ± 0.81	3.97 ± 0.81	4.14 ± 0.55	4.07 ± 0.52	4.21 ± 0.65	4.21 ± 0.71	4.18 ± 0.60	.474

Note: N/M±SD; superscripted letters in rows denote significant differences between indicated groups at 5% error level; Last column: significance level of χ^2 or ANOVA.

3.2. Effects of air ventilation regime and occupancy on comfort

The different comfort aspects were rated medium to good in all experimental groups (see supplement part C), and a significant main effect of occupancy in all ANCOVA was found. Except for comfort regarding temperature, all other comfort aspects were rated better in the half-occupied conditions (Table 3 and Fig. 2), with comfort regarding privacy and space showing large effect sizes (partial $\eta^2 = 0.443$ and 0.164, respectively). Comfort regarding temperature was the only comfort aspect with lower ratings in the half-occupied conditions and a medium-sized main effect of ventilation regime and a corresponding interaction between occupancy and ventilation regime. It mirrors closely the environmental temperature conditions during the experimental sessions, which could not be maintained at 23 °C for technical reasons (Norrefeldt et al., 2021) and varied between 21.8 °C and 25.4 °C (Table 1). Bonferroni adjusted group comparisons show that in the half-occupied conditions temperature is significantly rated highest in the Max. CO_2 ventilation regime with 23.6 °C (3.87, 95% CI: 3.69, 4.05) compared to ASHRAE half (3.57, 95% CI: 3.34, 3.76), ASHRAE (3.45, 95% CI: 3.27, 3.63) and to baseline condition (3.30, 95% CI: 3.12, 3.49) with no significant differences between these three. In the fully occupied conditions, the baseline ventilation regime with 21.8 °C is the driver of the interaction with lowest comfort ratings (2.88, 95% CI: 2.68, 3.10) compared to ASHRAE (3.61, 95% CI: 3.42, 3.81), ASHRAE half (3.43, 95% CI: 3.22, 3.64) and Max. CO_2 (3.52, 95% CI: 3.32, 3.72). A significant interaction effect between measurement time and occupancy also shows that the satisfaction with temperature decreased over time in the fully occupied conditions but remained stable over time in the half-occupied conditions.

Main effects of the ventilation regime at 5% error level were found for the general comfort rating, comfort regarding privacy, and comfort regarding air quality. Corresponding interaction effects between occupancy and ventilation regime occurred for general comfort ratings and air quality-related comfort (Fig. 2). Posthoc group comparisons show that all of these effects are consistently driven by lowest comfort ratings in the experimental group ASHRAE/half-occupied. For general comfort ratings, ASHRAE condition participants reported lower comfort (3.07, 95% CI: 2.88, 3.26) than baseline participants (3.45, 95% CI: 3.25, 3.64), ASHRAE half participants (3.48, 95% CI: 3.28, 3.68) and Max. CO_2 participants (3.67, 95% CI: 3.47, 3.87) in the half-occupied conditions whereas no differences were found in the fully occupied conditions (Baseline: 3.07, 95% CI: 2.88, 3.26; ASHRAE: 3.11, 95% CI: 2.93, 3.30; ASHRAE half: 3.20, 95% CI: 3.00, 3.04; Max. CO_2: 3.04, 95% CI: 2.85, 3.24). For privacy- and air quality-related comfort, the same pattern was found except that differences between ASHRAE and ASHRAE half, half-occupied conditions are not significant (privacy: ASHRAE: 3.75, 95% CI: 3.59, 3.92; ASHRAE half: 3.97, 95% CI: 3.79, 4.14; air quality: ASHRAE: 3.26, 95% CI: 3.17, 3.48; ASHRAE half: 3.55, 95% CI: 3.39, 3.70). Reasons for this could not be determined as neither environmental factors (Table 1) nor participant characteristics (Table 2) show any peculiarities for this group.

In terms of our hypotheses, for comfort outcomes, an independent main effect of the proximity of other passengers is confirmed, i.e., participants experienced higher comfort in the half-occupied conditions except for temperature-related comfort where we could not maintain 23 °C for technical reasons. However, results for an independent effect of air quality and its interaction with occupancy are inconclusive. The effects were produced by only one experimental group and neither the highest nor lowest recirculation air rate group; the hypothesized linear development has to be rejected.

3.3. Effects of air ventilation regime and occupancy on health symptoms and sleepiness

Participants in every condition and at different measurement times reported very low intensities of symptoms between on average 2,5% of sum scale for respiratory symptoms and 7,9% of sum scale for skin-/eye-related symptoms (see supplement part C). Only one significant main effect and one interaction were found. General health symptoms decreased significantly over time independent of occupancy and ventilation rate (small-sized main effect of measurement time F(2,534) = 3.98, p = .019; Fig. 3). For respiratory symptoms, a small-sized interaction effect between occupancy and ventilation regime occurred (F (3,541) = 3.76, p = .011). Bonferroni-adjusted posthoc comparisons show that the interaction is caused by differences between ventilation groups in the half-occupied conditions. There are no differences between the different recirculation air rates in the fully occupied conditions. In the half-occupied conditions again the ASHRAE group was responsible for the effect: ASHRAE group values (14.27, 95% CI: 10.90, 17.63) are significantly higher than Max. CO_2 (7.00, 95% CI: 3.56, 10.88). Overall, analyses of variance only show very few effects of occupancy and ventilation regime on health symptoms. Consequently, our hypotheses of independent main effects of occupancy and ventilation regime have to be rejected regarding self-reported health symptoms.

Sleepiness is one of the subjectively most often reported effects of stale indoor air. As with health symptoms, drowsiness and dullness, difficulty concentrating, and projection of physical impairment subscales showed relatively low levels (see supplement part C) across all experimental groups. Means show a curvilinear development of drowsiness and dullness over the five measurements with lowest values in the middle of the simulated flight. This effect is not significant. In addition, a significant interaction between occupancy and ventilation regime for drowsiness and dullness occurred (F(3,536) = 4.20, p = .006) with no differences between the ventilation regimes in the half-occupied

Table 3
Effects of air ventilation regime and occupancy on comfort.

	Measurement time (MT)		Occupancy		Ventilation Regime		MT X Occupancy		MT X Ventilation Regime		Occupancy X Ventilation Regime	
	F(df)	p	F(df)	p	F(df)	p	F(df)	p	F(df)	p	F(df)	p
General comfort rating	0.56 (1,499)	.453	21.46 (1,499)	.000***	2.95 (3,499)	.032*	4.38 (1,499)	.037*	0.40 (3,499)	.754	4.04 (3,499)	.007**
Comfort Privacy	0.33 (1,543)	.563	431.52‡ (1,543)	.000***	2.91 (3,543)	.034*	0.28 (1,543)	.598	0.25 (3,543)	.864	1.21 (3,543)	.304
Comfort Space	0.96 (1,542)	.328	106.42‡ (1,542)	.000***	1.26 (3,542)	.288	1.22 (1,542)	.269	0.74 (3,542)	.531	0.62 (3,542)	.603
Comfort Temperature	0.02 (1,542)	.884	7.53 (1,542)	.006**	*14.30* (3,542)	.000***	12.34 (1,542)	.000***	1.16 (3,542)	.326	3.92 (3,542)	.009**
Comfort Air Quality	0.01 (1,543)	.910	13.59 (1,543)	.000***	2.77 (3,543)	.041*	3.08 (1,543)	.080^{+}	2.36 (3,543)	.071^{+}	4.53 (3,543)	.004**

Note: Results of analyses of variance with repeated measures, models controlled for age, sex, BMI, smoking, sleep quality before exposure, health status, multiple chemical sensitivity: F(df) = F-value (degrees of freedom), p = level of significance: $+p \leq .10$; $*p \leq .05$; $**p \leq .01$; $***p \leq .001$; ‡ at least medium-sized effect (partial $\eta^2 \geq 0.06$).

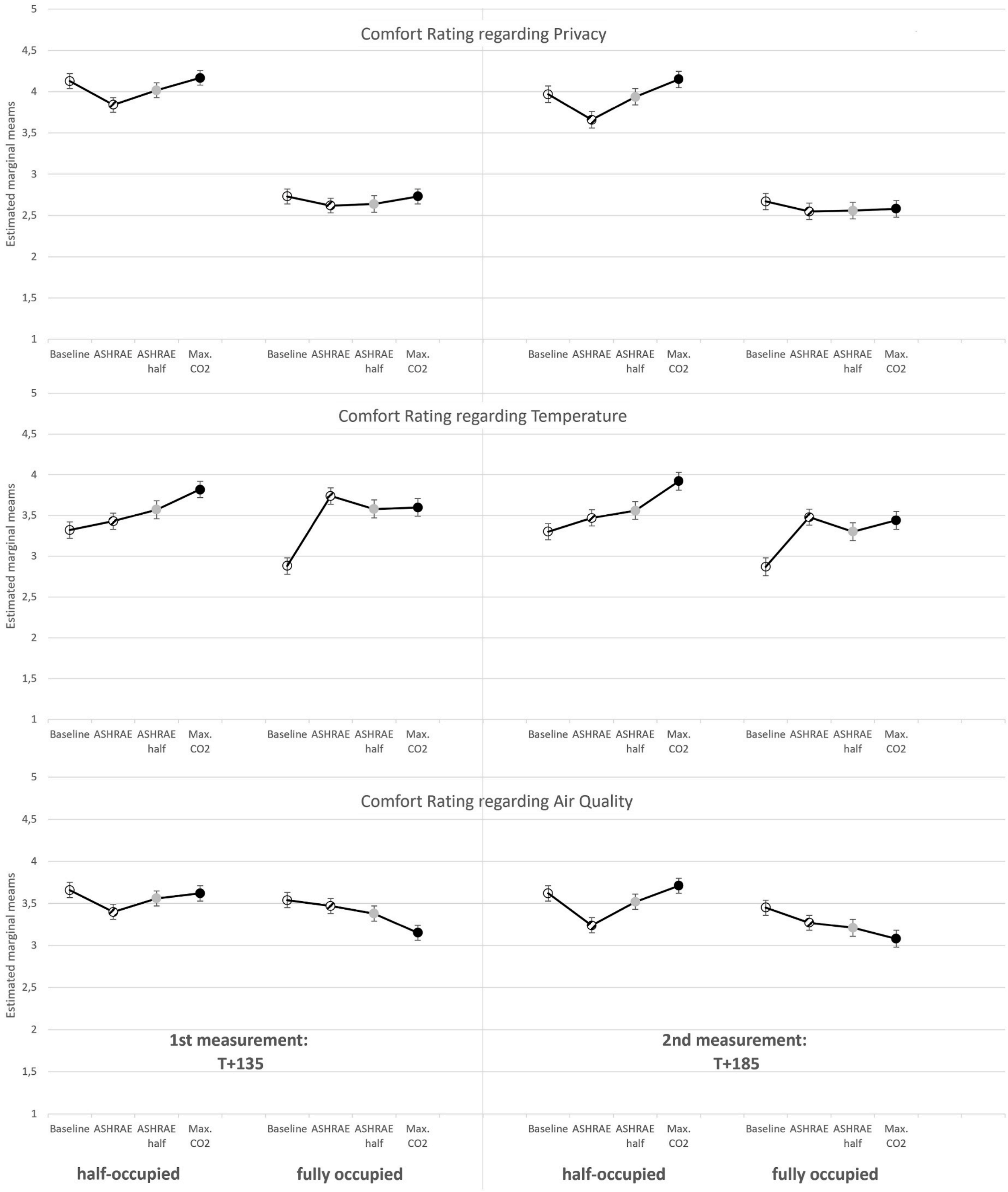

Fig. 2. Estimated marginal means for comfort ratings of different environmental aspects in groups and at different measurement times.

conditions but increasing drowsiness and dullness with increasing recirculation air rates in the fully occupied conditions (Fig. 4). This is mainly driven by the difference between baseline and Max. CO_2 condition according to the posthoc group comparisons (half-occupied: Baseline: 26.73, 95% CI: 22.13, 31.33; ASHRAE: 29.67, 95% CI: 25.18, 34.16; ASHRAE half: 23.48, 95% CI: 18.76, 34.16; Max. CO_2: 23.44, 95% CI: 18.95, 27.94; fully occupied: Baseline: 22.00, 95% CI: 17.63, 26.37; ASHRAE: 23.54, 95% CI: 19.25, 27.84; ASHRAE half: 24.69, 95% CI: 20.07, 29.32; Max. CO_2: 31.85, 95% CI: 27.37, 36.34).

A linear increase over time independent of occupancy and ventilation rate could be seen for the subscale difficulty of concentration ($F(4,536) = 2.53$, $p = .040$). No other effects could be observed.

In terms of our hypotheses, there is only one relevant moderation effect for the scale drowsiness and dullness. Independent influences of occupancy and ventilation regime could not be observed, but drowsiness and dullness of participants was higher with higher recirculation air rate only in conditions with higher proximity of other participants.

3.4. Effects of air ventilation regime and occupancy on physiological parameters

Heart rate and HRV parameters in the different experimental conditions are presented in Tables 4 and 5. As individual rest measures were taken into account through residuals, descriptive values are hard to interpret. In order to ease understanding of metrics and comparison with values from literature, these are projected to means in Figs. 5–9. All five

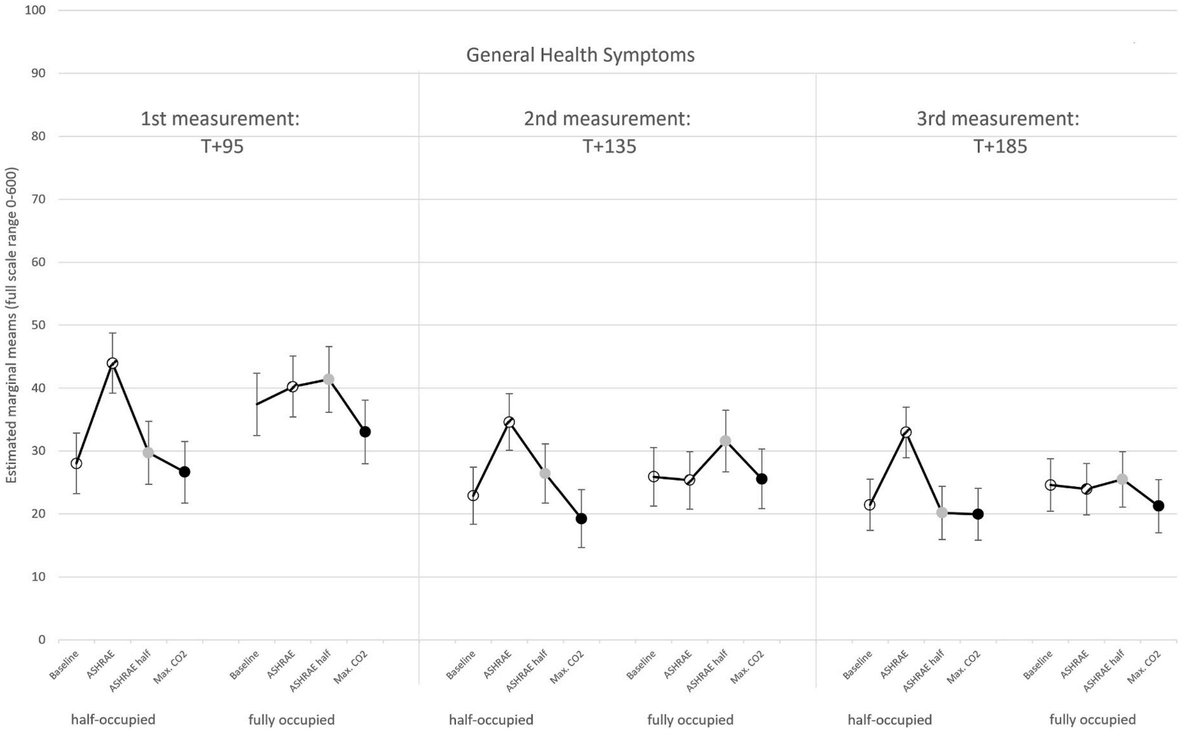

Fig. 3. Estimated marginal means for general health symptoms in groups and at different measurement times.

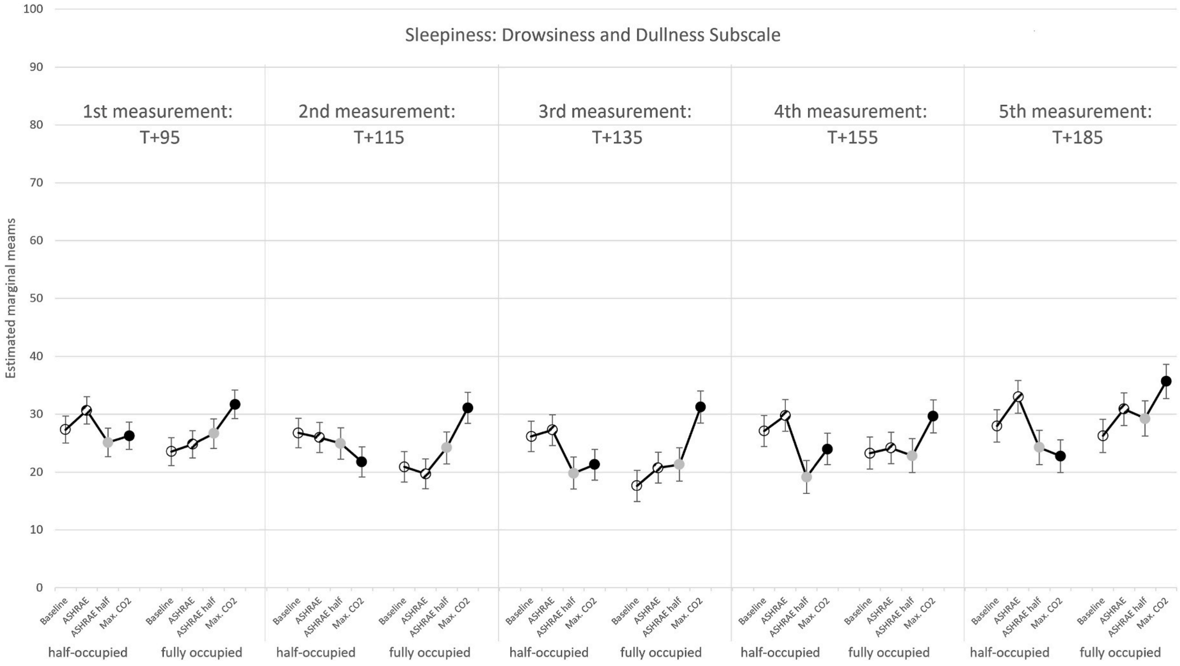

Fig. 4. Estimated marginal means for drowsiness and dullness in groups and at different measurement times.

physiological measures presented show significant main effects of occupancy (only trend for SDNN). In addition, for average HR, RMSSD, and SDNN, main effects of ventilation regime and interactions between the two experimental factors were found.

Average HR in the half-occupied conditions only varied between 71.7 bpm (ASHRAE half) and 72.9 (baseline) bpm in the different ventilation rate conditions (Fig. 5) and was significantly higher in the fully occupied conditions with values between 74.7 bpm (baseline) and 80.5 bpm (Max. CO_2). Bonferroni-adjusted posthoc group comparisons show no significant differences in the half-occupied conditions but significantly lower HR in the baseline ventilation rate (−1.00; 95% CI: −1.92, −0.08) compared to ASHRAE (1.18; 95% CI: 0.29, 2.08), ASHRAE half (2.10; 95% CI: 1.13, 3.07) and Max. CO_2 (1.24; 95% CI: 0.32, 2.16) in the fully occupied conditions.

RMSSD as a parameter of short-term HRV showed higher values (better adaptability) between 26.9 ms (Max CO_2) and 33.1 ms (ASHRAE half) in the half-occupied conditions without an influence of ventilation regime. The overall lower values in the fully occupied conditions

Table 4
Descriptive values of heart rate and heart rate variability parameters in air ventilation regime and occupancy groups.

Dependent variable	Baseline; half-occupied	ASHRAE; half-occupied	ASHRAE half; half-occupied	Max. CO_2; half-occupied	Baseline; fully occupied	ASHRAE; fully occupied	ASHRAE half; fully occupied	Max. CO_2; fully occupied
	EMM±SE	EMM±SE	EMM±SE	EMM±SE	EMM±SE	EMM±SE	EMM±SE	EMM±SE
Average Heart Rate	−0.92 ± 0.45	−0.29 ± 0.44	−0.34 ± 0.45	−1.51 ± 0.46	−1.16 ± 0.46	1.11 ± 0.45	2.14 ± 0.49	1.30 ± 0.46
RMSSD	0.04 ± 0.02	0.02 ± 0.03	0.03 ± 0.03	0.01 ± 0.03	0.10 ± 0.03	0.01 ± .03	−0.11 ± 0.03	−0.11 ± 0.03
SDNN	0.02 ± 0.02	0.02 ± 0.02	−0.01 ± 0.03	0.03 ± 0.03	0.08 ± 0.03	0.01 ± 0.03	−0.07 ± 0.03	−0.09 ± 0.03
LF/HF Ratio	−0.35 ± 0.12	−0.15 ± 0.12	−0.35 ± 0.13	−0.37 ± 0.13	0.18 ± 0.13	0.37 ± 0.12	0.22 ± 0.13	0.52 ± 0.15
Summary Measure: Recovery Time	5.00 ± 3.70	5.80 ± 3.72	5.75 ± 3.94	2.08 ± 3.86	5.20 ± 3.86	−2.13 ± 3.78	−8.99 ± 4.09	−15.0 ± 4.52

Note: Estimated marginal means and standard errors (EMM±SE) from analyses of variance, models controlled for age, sex, BMI, smoking, length of measurement (except for HR); unstandarized residuals: Values during exposure with rest measure partialled out.

Table 5
Effects of air ventilation regime and occupancy on heart rate and heart rate variability parameters.

	Occupancy		Ventilation Regime		Occupancy X Ventilation Regime	
	F(df)	p	F(df)	p	F(df)	p
Average Heart Rate	24.68 (1,549)	.000***	6.53 (3,547)	.000***	4.41 (3,547)	.004**
RMSSD	7.85 (1,549)	.005**	8.93 (3,547)	.000***	6.32 (3,547)	.000***
SDNN	2.99 (1,549)	.084^{+}	6.01 (3,547)	.000***	4.46 (3,547)	.004**
LF/HF Ratio	48.36‡ (1,549)	.000***	1.17 (3,547)	.319	0.92 (3,547)	.430
Summary Measure: Recovery Time	12.66 (1,549)	.000***	2.99 (3,547)	.031*	1.91 (3,547)	.127

Note: Results of analyses of variance, models controlled for age, sex, BMI, smoking, length of measurement (except for HR): F(df) = F-value (degrees of freedom), p = level of significance: +p ≤ .10; *p ≤ .05; **p ≤ .01; ***p ≤ .001; ‡ at least medium-sized effect (partial $\eta^2 \geq 0.06$).

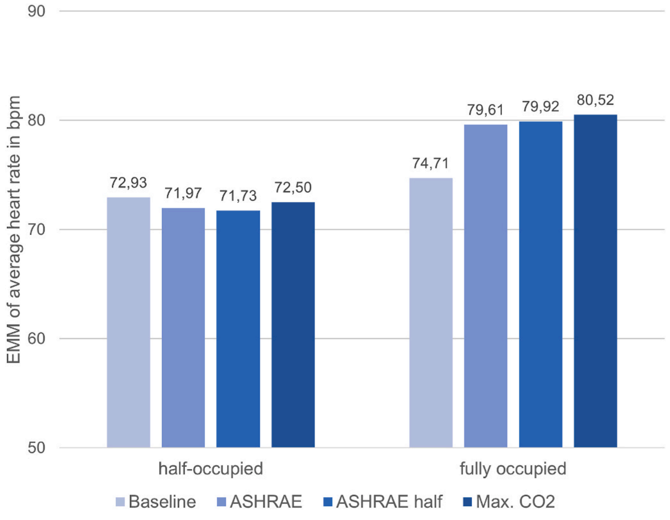

Fig. 5. Average heart rate residuals projected to means (in bpm).

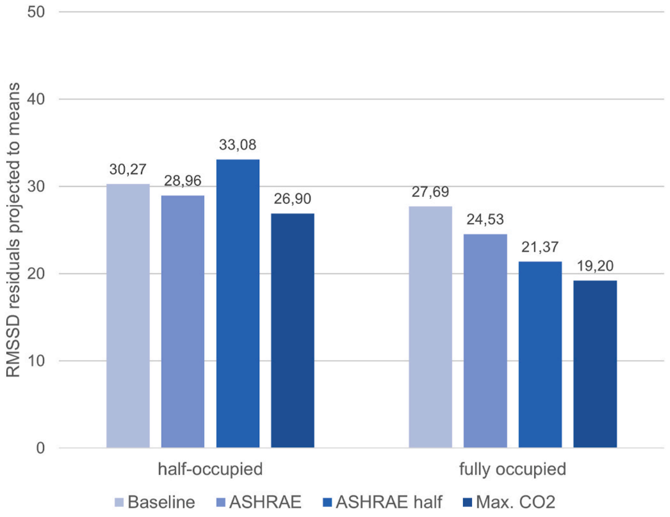

Fig. 6. RMSSD residuals projected to means.

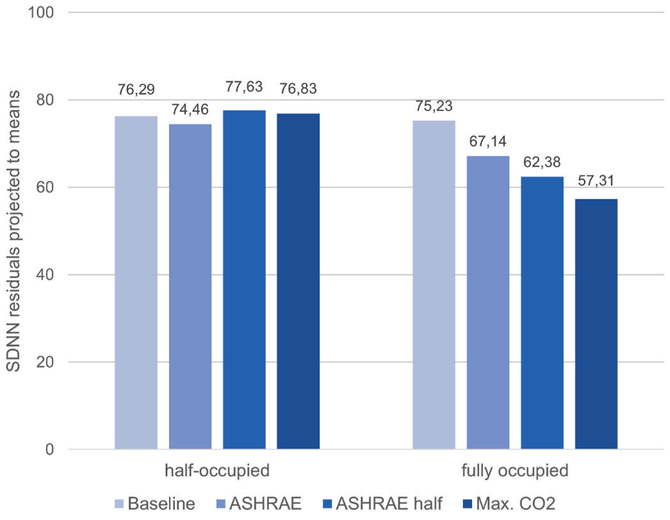

Fig. 7. SDNN residuals projected to means.

between 19.2 ms (Max CO_2) and 27.7 ms (baseline) (Fig. 6), however, are impacted by recirculated air rate. There is a linear decline of RMSSD with increasing recirculation rates in the fully occupied conditions (Baseline: 0.09, 95% CI: 0.03, 0.14; ASHRAE: 0.00, 95% CI: −0.06, 0.06; ASHRAE half: −0.11, 95% CI: −0.18, −0.05; Max. CO_2: −0.07, 95% CI: −0.18, 0.04). In general, RMSSD of all experimental groups are within norm values reported for short-term (45 ± 15) and 24 h measurements, although the value of participants in the Max. CO_2 fully occupied condition is at the lowest end of the reported short-term range (19–75) (Nunan et al., 2010; Shaffer and Ginsberg, 2017; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996.).

SDNN as a parameter that can be interpreted as a longer-term indicator of stress shows a similar pattern of results as RMSSD. It varied between 74.5 ms (ASHRAE) and 77.6 ms (ASHRAE half) in the half-

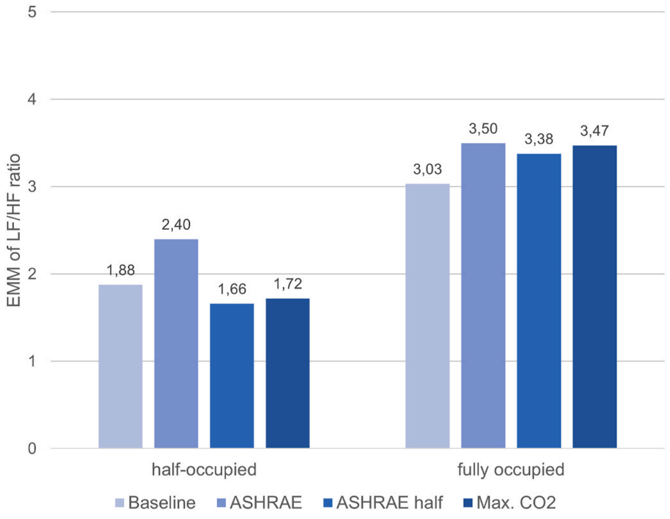

Fig. 8. LF/HF ratio residuals projected to means.

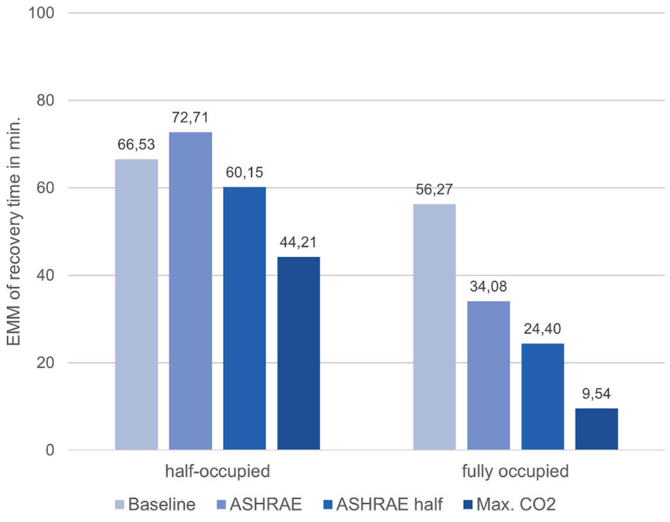

Fig. 9. Recovery time residuals projected to means (in minutes).

occupied condition and between 75.2 ms (baseline) and 57.3 ms (Max. CO_2) in the fully occupied condition (Fig. 7). There is only a trend for an occupancy main effect; however, the ventilation main and the interaction effect are more or less identical to RMSSD results. Bonferroni-adjusted group comparisons show that whereas the different ventilation regimes did not differ within the half-occupied condition, there was a linear decrease of SDNN in the fully occupied conditions with increasing recirculation air rate (Baseline: 0.09, 95% CI: 0.03, 0.15; ASHRAE: 0.02, 95% CI: −0.04, 0.08; ASHRAE half: −0.06, 95% CI: −0.13, 0.01; Max. CO_2: −0.10, 95% CI: −0.22, 0.01). SDNN values in all experimental groups are on the high side of the norm range for short-term measurements (45 ± 15, range 32–93, Nunan et al., 2010) but lower than values reported for 24 h measures (160 ± 40 (men), 147 ± 36 (women), Aeschbacher et al., 2017).

Analyses of variance for the frequency-based LF/HF ratio parameter of HRV show a large-sized main effect of occupancy with higher values reflecting stress in the fully occupied conditions (between 3.0 and 3.5) and lower values in the half-occupied conditions (between 1.7 and 2.4, see Fig. 8). There are no (differential) effects of the experimental factor ventilation regime. In general, LF/HF ratios in all experimental groups are within ranges reported in the literature for short-term measurements (2.8 ± 2.6, range 1.1–11.6, Nunan et al., 2010).

The summary measure recovery time segments the data into different coherent periods, excludes physical activity segments and detects times when parasympathetic activity is dominating the data. Results from the analysis of variance show again a significant main effect of occupancy: Participants in the half-occupied cabin experienced more recovery time (between 44.2 and 72.7 min) than participants in the fully occupied cabin (between 9.5 and 56.3 min, see Fig. 9). Moreover, a main effect of ventilation regime shows that participants in groups with higher recirculation air rates experienced less recovery than participants in groups with low recirculation air rates. Bonferroni-adjusted posthoc group comparisons showed that this effect was caused by a significant difference between baseline and Max CO_2 conditions with the other two ventilation regimes in between (Baseline: 5.10, 95% CI: −0.13, 10.33; ASHRAE: 1.83, 95% CI: −3.40, 7.07; ASHRAE half: −1.62, 95% CI: −7.28, 4.04; Max. CO_2: −6.45, 95% CI: −12.49, −0.41). As Fig. 6 illustrates, the magnitude of declining recovery time with higher recirculation air rates was more than twice as big for fully occupied than for half-occupied conditions.

In sum, physiological (stress) parameters were the outcomes most often showing the hypothesized relations. For all five parameters, results show that a higher proximity of other passengers leads to higher stress reactions and lower recovery. HR, RMSSD, SDNN, and relaxation time are additionally impacted by ventilation regime either as a main effect of a linear decrease in recovery with higher recirculation air rates or as effects moderated by the proximity of others with higher stress occurring with increasing recirculation air rates only in the fully occupied conditions.

4. Discussion

Lowering outside air rates in aircraft cabins and simultaneously increasing recirculation air rates to maintain the total air supply rate might help reduce the carbon footprint of flying to save energy by using more kerosene for thrust. The main objective of the presented study was to investigate if this can be done without impairing health and well-being of passengers. Within existing limits of CO_2 for aircraft cabins (e.g., FAA, 2019), four air ventilation regimes were tested, letting VOCs and relative humidity develop naturally with increasing recirculation air rates. That is, with increased recirculation air there is less outside air for dilution, and VOCs and H_2O produced are recirculated and not diluted/removed, so over time the concentrations build up. We also systematically varied the probably most dominant feature of aircraft cabins – the proximity of other passengers. To the best of our knowledge, this is the first large-scale randomized controlled trial examining this topic, additionally relevant for any other densely occupied space.

In general, all reported health and well-being measures were within average to good (subjective measures) or normal ranges (physiological measures), so it seems safe to assume that none of the examined experimental conditions caused clearly adverse health effects. For comfort perceptions as part of passengers' well-being, we only found the impact of occupancy independent of ventilation regime in the direction that participants reported lower comfort in the fully occupied cabins. The only notable exception from this pattern was the comfort rating regarding temperature that closely followed the cabin temperature (and related relative humidity), which were higher in the fully occupied cabin with high recirculation regimes. Grün et al. (2008) showed similar effects on thermal comfort rating in the range between 20.7 °C and 24.5 °C in simulated 7-h flights: Frequently measured comfort (every 30 min) decreased for 20.7 °C, remained unchanged at 22.9 °C, and increased at 24.5 °C. In addition, they also showed interrelations between temperature and other aspects like noise perception. However, results for our study's other (comfort) outcomes showed no development analogous to thermal comfort.

A number of observed differences depended on participants' ratings in the ASHRAE half-occupied condition. They showed the lowest ratings compared to the other groups leading to a rejection of the possibility of linear deterioration with increasing recirculation air rates. Although we made a thorough comparison of the involved sessions and dates from environmental data and situational aspects to group composition and ratings in the individual sessions, none of these analyses gave any indication that something in this experimental condition was so different from the other ones that the data could not be considered reliable. Physiological HR and HRV data were not impacted by this peculiarity and showed the expected relations: Close proximity of others exacerbated the negative linear developments with increasingly poorer air quality. These clear, objectively measured, stress-related effects contrast the overall good levels of subjectively reported health and well-being. Especially the self-reported highest sleepiness in the fully occupied Max. CO_2 condition that is in line with previous research (e.g., Vehviläinen et al., 2016; Zhang et al., 2017), although not found by others (e.g., Pang et al., 2021), is intriguing as objectively measured cardiovascular recovery time is the lowest in this condition. It underpins the stress assumption of feeling exhausted without being able to relax on a physiological level.

Considering all results, the closeness or proximity of other persons might have played an important role, perhaps even a crucial one. In line with the findings from Lewis et al. (2017) on the negative effect of the invasion of personal space on passengers' comfort as well as the theoretical considerations of Hall (1966), showing how the violation of the need for privacy leads to strain and behavioral modifications, our results confirm the strong impact of the proximity of others. However, especially the interaction effect between occupancy and air ventilation regime on physiological stress parameters seems to exclude a purely psychological mechanism as only the fully occupied conditions showed increases in stress with higher recirculation air rates. A potential explanation for this could be that the proximity of others also changed some physical environmental conditions that enhanced air quality effects. Temperature and relative humidity increased with increasing recirculation air rates and higher levels in the fully occupied conditions. However, subjective comfort ratings do not support these factors as responsible for the interaction on stress reactions. The comfort ratings also preclude any type of sensitization for environmental aspects due to the stress experienced by the proximity of others. Although our measurement devices for TVOC in the cabin were not set up to capture differences on a localized level (e.g., seat), another explanation could be that the higher amounts of VOCs in the higher recirculation air regimes might be aggravated if one directly inhales "clouds" of VOCs from others sitting in close proximity (either via body odors or exhaled breath, that is, bioeffluents), while otherwise these VOCs would have been diluted if there had been sufficient distance between them. Other reasons for the interaction of occupancy and ventilation rate are conceivable, but further research is needed to investigate this in more detail. The main result is that the effects on heart rate (variability) found are systematic and relatively strong, so our RCT shows that occupancy is an important (modifying) factor that has been neglected in previous research on air quality.

However, there are limitations. First of all, we could not technically control all environmental conditions, especially temperature varied between conditions because of the available cooling power of the recirculation heat exchanger (Norrefeldt et al., 2021). Secondly, a double-blinded study would have been preferable to eliminate potential bias from investigator behavior. Due to the high technical effort, this was not feasible, and strict scripts for announcements and reactions in the cabin were used to ensure comparable investigator behavior in all experimental conditions. Thirdly, participating as passengers, participants experienced a sedentary situation without the necessity to perform a task or activity beyond the study tasks. Therefore, generalization of results to other contexts, e.g., cabin crew work, or to situations at ambient pressure, like, e.g., air-conditioned open-plan offices, is difficult for the factor air quality. Nevertheless, the psychological effects of occupancy are probably not affected and can be generalized (as, for example, studies from open-plan offices suggest; Herbig et al., 2016; James et al., 2021). An additional limitation for generalizability is that our study included only reasonably healthy adults whereas real passengers are more heterogeneous and include children or persons with disabilities or diseases. Although we assume that severely sick persons would not fly under normal circumstances and although there are special provisions regarding this (fit-to-fly medical certificates), these vulnerable groups also have to be considered before changes in ventilation regimes are introduced. Fourthly, this study only investigated the effects of acute exposure of about 3.5 h (at the planned exposure conditions); effects of longer exposures or repeated exposures cannot be inferred. Especially regarding HRV, effects of chronic stress have been shown (e.g., Chandola et al., 2010; Järvelin-Pasanen et al., 2018; Jarczok et al., 2013). And fifthly, VOCs in our study mostly contained bioeffluents and hardly any background from the cabin or the aircraft. Their absence limits the generalizability of our results to all flight conditions or frequent flyers.

The Sars-CoV-2 pandemic has led to an increased attention to aerosols in the air. This highlights another potential limitation that is not inherent to our study but for the general goal of reducing the carbon footprint of flying by changing ventilation rates: the question whether higher recirculation rates facilitate the spread of airborne viruses. This depends on the technical equipment of the aircraft. Even before the pandemic, ASHRAE standard 161 stated that recirculated air in the aircraft shall pass a high efficiency particulate air (HEPA) filter before being reinjected to the cabin, and therefore recirculation air can be considered as clean with regard to particulates. If a HEPA filter is present (as in most modern, large commercial aircraft), model calculations show that the risk of transmission does not increase. For example, Shen et al. (2021) could show an infection risk reduction of HEPA filter equivalent to risk reduction of 100% outside air. However, Schmohl et al. (2022) conducted tests in a realistic cabin with and without HEPA filter in the recirculation line and showed that two factors impact the particle and hence aerosol concentration distribution in the aircraft: 1) the distance from the emitter and 2) the use of HEPA filtration. Especially seats farther away from the aerosol emitter show to benefit from the HEPA filtration, that is, similar to other indoor or outdoor environments being physically (very) close to an emitter increases the risk of infection by airborne viruses. Today's HEPA filters have a typical lifetime of 5000 h. For adopting an increased recirculation rate, these would have to be redesigned (Zavaglio et al., 2019) or changed more frequently due to higher load.

5. Conclusion

The answer to the major question on whether outside air rates in aircraft cabins be reduced to lower the carbon dioxide footprint of flying without compromising passenger health and well-being considering the limitations of the present design is tentatively positive but only for half-occupied cabins; this can be done even to levels close to the limit values. Effect sizes show that occupation impacts passengers' responses much more than increasing recirculation air rate. Only if an aircraft is more or less fully occupied – which of course is also relevant for a lower carbon dioxide footprint - the ventilation regime plays a role and shows rather systematically decreasing health and well-being with increasing recirculation air rate. Nevertheless, for most parts the differences between ventilation regimes in the fully occupied cabin are small and reported health and well-being are rather good even with the highest recirculation air rate. However, the physiological data need to be taken more seriously. Although all parameters remain within normal ranges and everybody experiences this type of stress reaction every day, further research on other short-term reacting, stress-related outcomes potentially more relevant for health (like e.g., inflammatory markers) is needed to determine whether our results on the interaction between proximity of others and air quality should be a cause for concern.

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Ethics Approval

This study was approved by the Ethics Committee at the Faculty of Medicine, Ludwig-Maximilians-University, Munich, Germany (ID: 19–256).

Authors contributions

Britta Herbig: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition. Victor Norrefeldt: Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Project administration, Funding acquisition. Florian Mayer: Methodology, Investigation, Resources, Writing – review & editing, Project administration. Anna Reichherzer: Formal analysis, Writing – review & editing. Fang Lei: Methodology, Writing – review & editing. Pawel Wargocki: Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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