https://dx.doi.org/10.1016/j.buildenv.2022.109167

A study on human perception in aircraft cabins and its association with volatile organic compounds

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Abstract

More than 8 million people fly on commercial aircraft each day with approximately 5% having a pre-existing respiratory disease. Thus it is necessary to provide high air quality in aircraft to protect public health. Volatile organic compounds (VOCs) present in aircraft cabins are suspected to contribute to the reported complaints. We investigated concentrations of VOCs, air temperature, relative humidity, and CO_2 concentrations in a total of 46 flights, including 26 Chinese domestic flights and 20 international flights. We focused on the data from the cruising phase without meal serving in which the air supply and air recirculation were steady. A total of 284 passengers (i.e., 101 on international flights and 183 on Chinese domestic flights) were invited to participate in questionnaire surveys in this phase. We performed a linear mixed model analysis by controlling for potential confounders (age, gender, smoke habits, and history of allergy) to study associations between VOCs exposures and passengers' complaints. Xylene was significantly associated with irritations of the eyes, nose, and throat on both international and domestic flights, with antilog beta values from 1.12 to1.28 (p<0.05). The association of some aldehydes (i.e., nonanal, decanal, and heptanal), which are potential oxidation products with ozone, with passengers' sensory irritations was also significant, especially during international

flights (antilog beta values: 1.19-1.22). It indicates that VOCs, especially xylene and aldehydes, in aircraft cabins may influence the perceived indoor air quality and complaints among passengers.
Keywords Cabin air quality, In-flight measurement, Questionnaire survey, Subjective perceptions, VOCs

1. Introduction

Nowadays, worldwide airplane transportation is increasing, reaching 4.34 billion global passengers by 2018 [1]. Substantial growth in the number of airline passengers presented a more serious challenge to creating a safe, healthy, and comfortable cabin environment [2,3]. Different from other built environments, the aircraft cabin environment has such unique factors as low relative humidity, low air pressure, extremely high occupant density, and potential exposure to air contaminants such as ozone and various organic chemicals [4-8].

Passengers have registered complaints about the aircraft cabin environment for decades. Spicer et al. found that 23.5 % of passengers in the cabin were dissatisfied with the odors [9]. Pierce et al. showed that the most serious complaints from crews and passengers in aircraft cabin environments were skin dryness, nose dryness, and eyes dryness [10]. Many studies have noted that fatigue and headache had a high proportion of passengers' perceptions according to the questionnaire [11-12]. A report issued by the U.S. Airliner Cabin Environmental Research (ACER) Program indicated that there was eye irritation (10.8%), blurred vision (7.5%), sinus congestion (29.0%), nose irritation (5.0%), sore throat (7.0%), cough (10.8%) and hoarseness (5.1%) among 3700 flight crew [13]. Compared to the general population, McNeely et al. observed higher rates of health outcomes such as fatigue in U.S. flight attendants due to undergoing a wide and unique range of adverse job-related exposures [14]. The low relative humidity typical of aircraft cabins has been implicated in causing many of the transient symptoms reported [15]. However, controlled exposure studies that mimic some of the air quality and environmental conditions on aircraft have suggested that volatile organic compounds (VOCs) present in aircraft cabins also contributed to the reported symptoms [16-17].

In an aircraft cabin environment, VOCs may be from combustion products leaking into the Environmental Control System (ECS), products used on aircraft for cleaning, human metabolic byproducts, and synthetic materials used in the cabin construction [18-20]. Some studies have addressed VOCs concentrations and species on aircraft cabins. Wang et al. [21] conducted VOCs tests in 14 single-aisle aircraft to assess the concentrations of BTEX (benzene, toluene, ethylbenzene, and xylene) and found their average concentrations were 14.78 $\mu g/m^3$, 29.84 $\mu g/m^3$, 7.04 $\mu g/m^3$ and 9.38 $\mu g/m^3$, respectively. Waters et al. [22] tested 36 flights on 11 aircraft types and found the predominant VOC was ethanol, followed by toluene and limonene. The team of Cranfield University sampled 5 target VOCs on 100 flights with 5 different aircraft types and found that the most abundant VOCs were limonene and toluene [23]. Guan et al. [24-25] conducted in-flight measurements on 107 flights and proposed 41 VOCs with a high detection rate (>50%) as key compounds in the cabin. However, few studies focused on the associations of VOCs with passengers' health and comfort. Dechow et al. measured the concentrations of VOCs during medium-distance and long-distance flights in the cabins of Airbus A310 and A340 aircraft [26]. In general, VOCs concentrations inside the cabin were lower as compared to other indoor locations, without relevance to health risks or comfort restrictions [27]. Spengler et.al [28] investigated the potential link between perceived passengers' discomfort and cabin environment conditions. Due to the small sample size of the study, the relationship between VOCs and passengers' complaints could not be identified.

In summary, a major limitation of most previous studies has been the lack of objective measurements of VOCs and passengers' health outcomes under actual flight conditions. In cases where such measurements have been included, the sample size has been quite limited with only descriptive statistics. No assessment of the extent of correlations between subjective and objective measures, for either cabin conditions or health symptoms. In our study, we systematically measured objective environmental parameters in aircraft cabins during flights mainly VOCs concentrations, and surveyed subjective perceptions among passengers. The study aims to explore the impact of VOCs on passengers' health and comfort and to determine the target VOCs that are relevant to human perceptions.

2. Methods

This study was carried out from July 2018 to June 2019 on a total of 46 flights. It consisted of measurements of cabin environmental parameters during the whole flight and questionnaire surveys on passengers' perceptions.

2.1 Flight selected

A total of 46 flights were investigated, including 20 international flights and 26 Chinese domestic flights. The flights were chosen randomly but intended to have broader coverage of aircraft model and duration. The basic information of the investigated flights is shown in *Table 1*. The type of aircraft covered dual-aisle aircraft (Boeing777, Boeing 787, Airbus 330, and Airbus 350) and single-aisle aircraft (Airbus320, and Boeing737). Among the 20 international flights, the flight duration ranged from 6 to 14 hours, while it was 1 to 4 hours for domestic flights.

Table 1 The information on flights.

Flight type	Numbers	Flight duration	Aircraft type （numbers）
International flights (long distance)	20	6-14 h	A320 (1) A330 (1) A350 (2) B787 (7) B777 (9)
Chinese domestic flights (short distance)	26	1-4 h	E190 (1) A320 (5) A330 (4) B737 (16)

2.2 Environmental parameter measurements

The environmental parameters measured during flight were air temperature, relative humidity, CO_2 concentrations, and VOCs.

2.2.1 Samplings and analysis of VOCs

Air was sampled in a breathing zone by placing the sampling device on the seat table or seatback pocket without blocking the air sampling port. The flight duration was divided up into five phases, including boarding, taking-off, cruising, meal/drink servicing, and landing phases. Carbonyls were actively sampled by a 2,4-dinitrophenylhydrazine (DNPH) cartridge [29-31]. The sample flow rate of carbonyls was 0.4 L/min. The total sampling air volume should be controlled between 1 L to 10 L, and the sampling time at any location should be no less than 5 minutes to eliminate the interference of sudden pollution sources. High-Performance Liquid Chromatography (HPLC) method was used to quantify the concentration of 11 carbonyls, i.e., formaldehyde, acrolein & acetone, propionaldehyde, 2-butanone, butyraldehyde, benzaldehyde, valeraldehyde, m&o-tolualdehyde, and hexanal.

Tenax-TA adsorption tubes were used to collect other VOCs in the air for analysis. The flow rate of the sampling pump was kept at 0.2 L/min for 20 minutes, and the total sampling volume was 4 L [29-31]. Gas Chromatography-Mass Spectrometer (GC-MS) method was used to quantify VOCs concentrations. Mixed standard VOC solutions with five compounds (benzene, toluene, acetic_acid, butyl_ester, ethylbenzene, p/m-xylene, styrene, o-xylene, and undecane) were quantified separately. Concentrations of other VOCs concentrations were quantified based on the response of toluene. The detection limit was 1 ng (i.e., concentration detection limit 0.25 ug/m^3) for each chemical compound. Half the value of the detection limit was assigned if the VOC concentration of the sample was below the detection limit. QA/QC (Quality Assurance/ Quality Control) and analysis method of GC-MS / HPLC refer to Yin et al. [32].

2.2.2 Measurements on air temperature, relative humidity, and CO_2

Indoor air temperature, humidity, and CO_2 concentrations were continuously monitored throughout the entire flight in breathing zones by using portable instruments. The specifications of the instruments are shown in *Table 2.* All the instruments were calibrated before the study.

Table 2 Specifications of portable instruments for cabin air quality monitoring.

Parameters	Resolution	Range	Monitor
Temperature	± 0.1°C	15°C-40°C	WSZY-2, Tianjian Huayi, China
Humidity	±5%	0%-70%	WSZY-2, Tianjian Huayi，China
CO_2 concentrations	± 1 ppm	0-5000 ppm	Telaire-7001D, GE, USA

2.3 Passengers' perceptions evaluations

Perceived indoor air quality and SBS symptoms among passengers were investigated by questionnaire, which was similar to those used previously in a series of the aircraft cabin and office studies to obtain subjective assessments of air quality and sick building syndrome (SBS) symptoms [5, 16-17, 33, 38]. Grading scales were used to describe the intensity of odour [34] and the irritation of the eyes, nose, and throat [35]. SBS symptoms were evaluated using visual-analogue scales [36], which are sensitive to small changes and independent of the subjects'recollection of past symptoms [37]. In our study, nine variables (as shown in *Table 3*) were assessed through a grading scale and visual analogue scale (as shown in *Figure 1*). Passengers should mark the corresponding position in the scale and we converted the mark into digital form for later analysis. These surveys on subjective assessment were repeated three times during international flights (i.e., 0-3 hours (earlier), 3-8 hours (middle), and 8-12 hours after take-off (late)) and two times during domestic flights (i.e., 0-1 hours (earlier) and 1-4 hours (late)). Information on passengers' age, gender, smoking habits, and allergy history was obtained through a background survey. Current health condition at boarding was self-reported by investigated passengers. Assessments from those who were not in a good health condition before boarding were excluded from further analysis. The Research Office at Tianjin University approved the study. Informed consent was obtained from all participants.

Table 3 Summary of subjective assessment variables and their specified values.

Terms	Range	Low value	High value
Assessments of air quality			
Odor intensity [a]	0——50	No odor	Overpowering odor
Nose irritation [a]	0——50	No irritation	Overpowering irritation
Throat irritation [a]	0——50	No irritation	Overpowering irritation
Eyes irritation [a]	0——50	No irritation	Overpowering irritation
Sick building syndrome symptoms			
Nose dryness [b]	0——100	Not dry	Dry
Skin dryness [b]	0——100	Not dry	Dry
Eyes dryness [b]	0——100	Not dry	Dry
Fatigue [b]	0——100	No tried	Tired
Headache [b]	0——100	No headache	Severe headache

[a] *Grading scale.*

[b] *Visual analogue scale.*

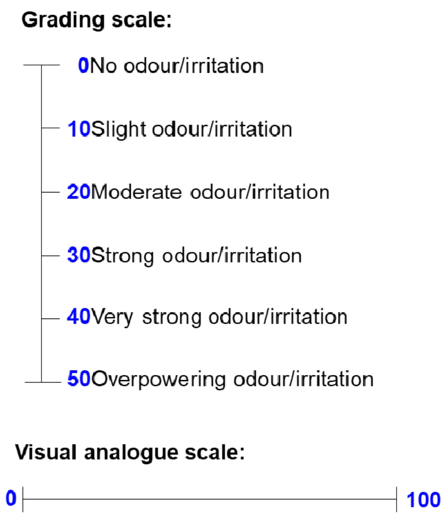

Figure 1 Scales used in the subjective assessment questionnaire.

2.4 Statistical analysis

We investigated the association between VOCs exposures and passengers' evaluations using a linear mixed model taking into account heterogeneity among international and domestic flights. To eliminate the co-influence of temperature, relative humidity, and CO_2 concentrations on the association between VOC and passengers' perception, we focused on the cruising phase without meal serving. The phase was defined as a level flight phase without special personnel activity, during which the air supply and air recirculation were steady and consequently temperature, humidity, and CO_2 concentrations were considered at a relatively stable condition. VOC data collected in time with the questionnaire survey during the cruising period were identified and involved in the linear mixed models. The concentration of individual VOC and passengers' perceptions were the input data in the linear mixed model analysis. Potential confounders such as passengers' age, gender, smoke habits, and history of allergy were adjusted. Data on perceptions were not normally distributed except for dryness perceptions (e.g., eyes/nose/skin dryness). Logarithmic conversion processing was performed for the above data on perceptions, except for dryness perceptions. VOCs concentrations were treated as continuous variables without any transformation. The associations between VOCs and perceptions were calculated and presented as antilog beta values with a 95% confidence interval (CI). We accept p-value < 0.05 as statistically significant. All statistical analyses were performed with STATA 16.0 software.

3. Results

3.1 Distribution of indoor environmental parameters

3.1.1 Temperature, relative humidity, and CO_2

Indoor air temperature, relative humidity, and CO_2 concentrations were continuously measured during flights.

Figure 2 shows the box plots of cabin air temperature on different flights during cruising phases. The average temperatures on different flights ranged from 21°C to 31°C, with relatively higher cabin air temperature on domestic flights (Domestic, 26.4°C; International, 24.3°C).

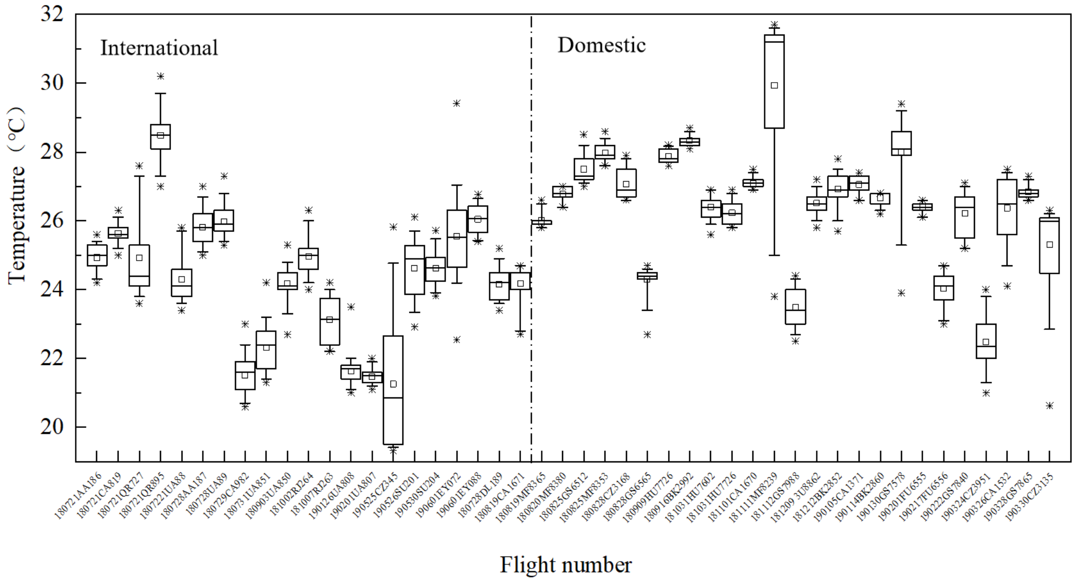

Figure 2 Temperature distributions in different flights during the cruising phase.

Figure 3 presents cabin air relative humidity distributions on different flights during the cruising phase. The relative humidity inside aircraft cabins was generally low. At the cruising phase, the average humidity in international flights ranged from 10% to 35%, while domestic flights had a range of 10%-40%.

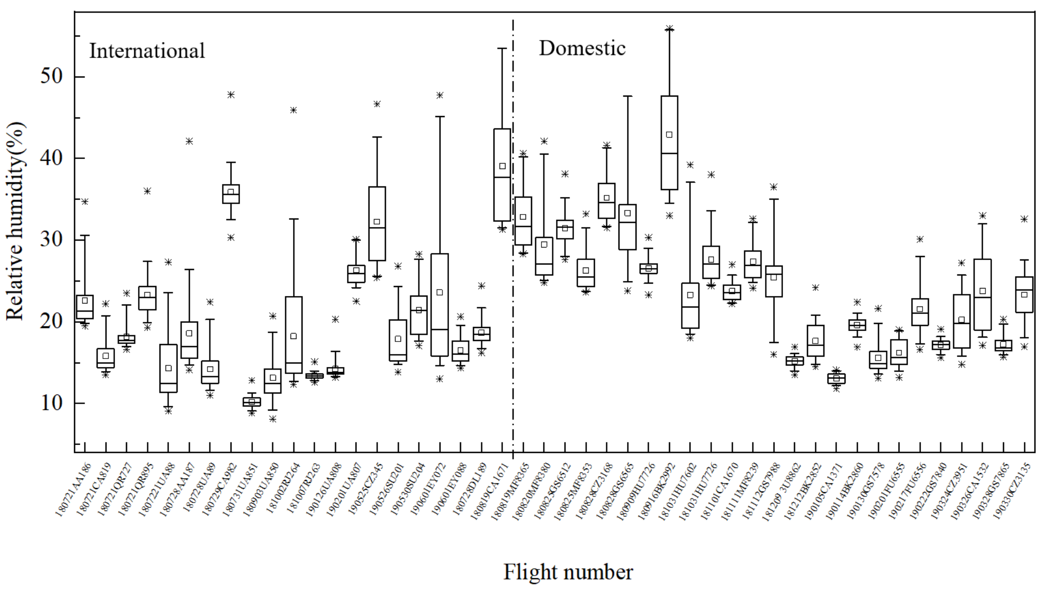

Figure 3 Relative humidity distributions in different flights during the cruising phase.

CO_2 concentrations were only measured in 36 flights, including 19 international flights and 17 domestic flights. CO_2 concentrations remained relatively stable in the cruising phase, with average concentrations below 1,500 ppm in 89% of flights. *Figure 4* presents the CO_2 distribution in different flights during the cruising phase. The average concentrations on domestic flights were in general higher than that on international flights（Domestic, 1310 ppm; International, 983 ppm）.

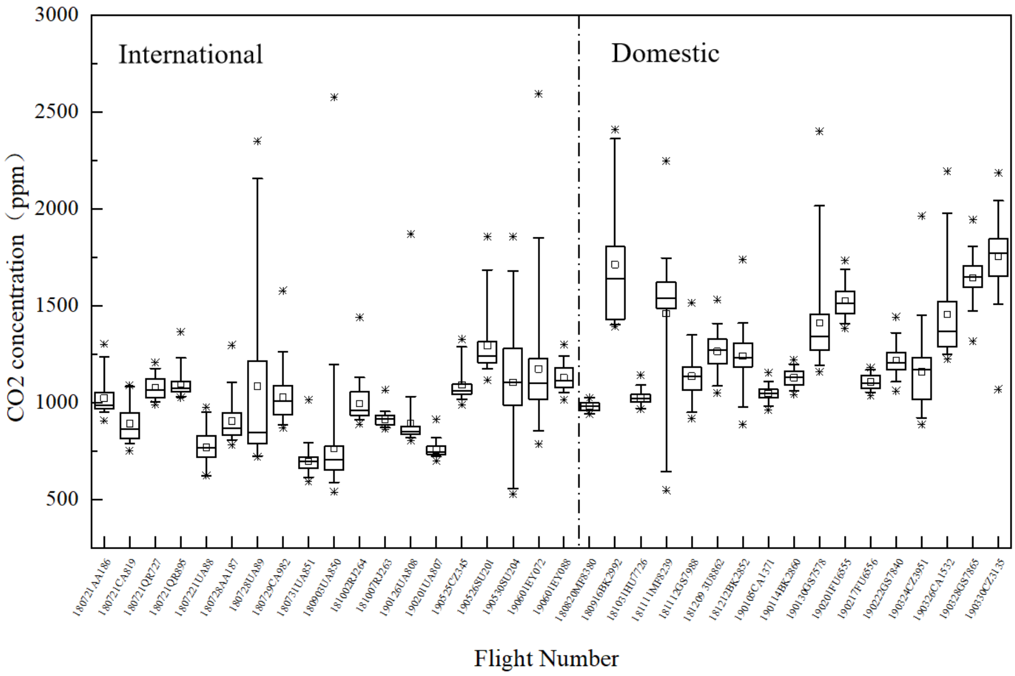

Figure 4 CO_2 concentrations distributions in different flights in the cruising phase.

3.1.2 VOCs concentrations

During the cruising phases of international and domestic flights, 16 VOCs with detection rates> 60% were detected respectively. Their concentrations are demonstrated in *Figure 5* and *Figure 6*. These VOCs were involved in the analysis of their associations with passengers' perceptions. The median VOCs concentrations on international flights were mainly distributed between 0-10 μ g/m^3, while it was less than 20 μ g/m^3 on domestic flights. In general, the concentration of pollutants on domestic flights was slightly higher.

Regarding to individual VOCs, concentrations of aldehydes were relatively higher, compared to others. For example, the median concentrations of heptanal, nonanal, and decanal on international flights were 5.5 μg/m^3, 3.6 μg/m^3, and 4.8 μg/m^3, while those on domestic flights 8.3 μg/m^3, 10.6 μg/m^3, 8.9 μg/m^3. For benzene series, toluene had a relatively higher concentration (median value= 3.7 μg/m^3 and 8.1 μg/m^3 in international and domestic flights), while concentrations of other benzene series such as ethylbenzene, xylene, and benzene during the cruising phase were between 1.4 μg/m^3 and 3.3 μg/m^3

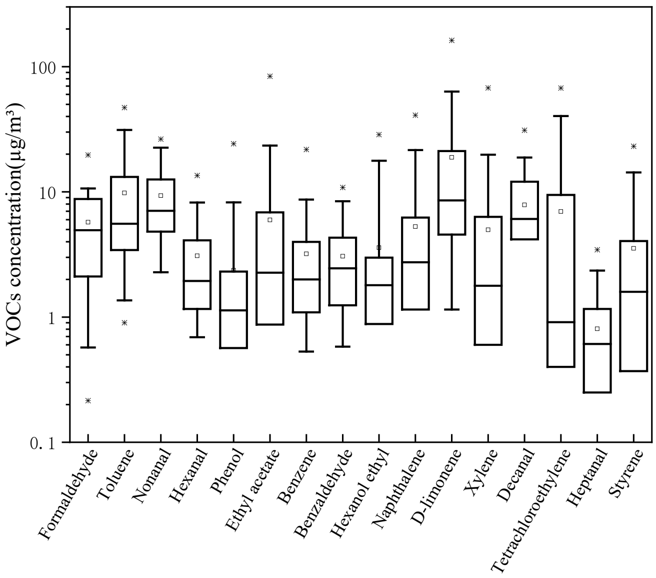

Figure 5 Concentrations of volatile organic compounds in international flights during the cruising phase.

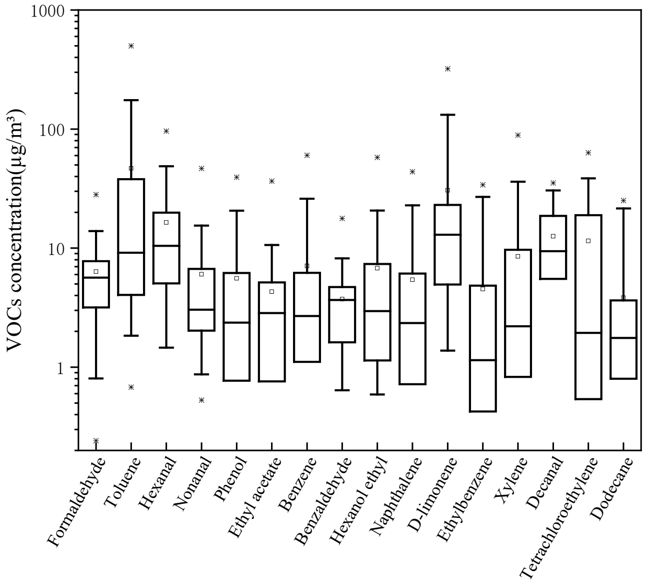

Figure 6 Concentrations of volatile organic compounds in domestic flights during the cruising phase.

3.2 Evaluation of passengers' perceptions

A total of 623 passengers (i.e., 246 on international flights and 377 on Chinese domestic flights) were invited to participate in questionnaire surveys on the whole flight. As mentioned above, we focused on the cruising phase without the meal serving. In this phase, 284 passengers (i.e., 101 on international flights and 183 on Chinese domestic flights) reported their health and comfort information. The results of an overall evaluation of passengers' perceptions are presented in the Supplementary Material. The background information of passengers is summarized in *Table 4*, which is collected during the cruising phase. Among the passengers investigated in the cruising phase-on international and domestic flights, 48.0% and 36.6% were females, 95.0% and 80.9% were current non-smokers, 78.2% and 78.6% had no allergies, and the mean age was 32.9 and 31.7 years, respectively.

Table 4 Background information of investigated passengers on international (n=101) and domestic flights（n=183）during the cruising phase.

Variable		International flights	Domestic flights
		n (%)	n (%)
Age (years)	<21	15 (14.9)	17 (9.6)
	21-35	50 (49.5)	103 (58.2)
	36-50	24 (23.7)	52 (29.4)
	>50	12 (11.9)	5 (2.8)
Gender	female	48 (48.0)	67 (36.6)
Smoke [a]	No	96 (95.0)	148 (80.9)
Allergy [b]	No	79 (78.2)	143 (78.6)

[a] *Data obtained by the question of "Do you smoke?".*

[b] *Data obtained by the question of "Have you ever had an allergy?", and the data were missing 1 questionnaire on domestic flights.*

Figure 7 shows that there was no significant difference between odor and sensory irritation on international and domestic flights. Passengers' subjective assessments of dryness perceptions, fatigue, and headache are shown in *Figure 8*. The higher the score of passengers' subjective assessment, the stronger the perceived intensity. On international flights, the reported intensity of dryness symptoms (median=70/64.5/63 in nose/skin/eyes dryness, respectively) and fatigue (median=52.5) was higher than the intensity of headache (median=22.5). On domestic flights, a similar trend was observed (median value: nose dry 67; skin dry 56; eyes dry 58; fatigue 50; and headache 18). In both international and domestic flights, passenger perception of dryness was a common problem, compared to other symptoms.

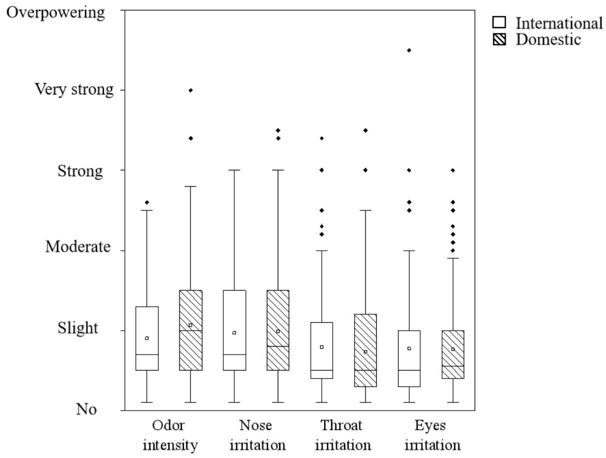

Figure 7 Evaluation of passenger odors and sensory irritation during the cruising phase.

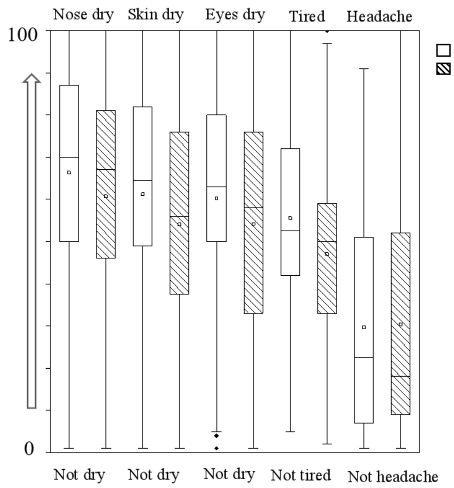

Figure 8 Evaluation of dryness perceptions, fatigue, and headache during the cruising phase.

3.3 Associations between VOC concentrations and passengers' perceptions

The associations between VOCs and perceptions are presented as antilog beta values with a 95% confidence interval (CI), as shown in *Table 5 (a)-(b)*.

During international flights, toluene, ethylbenzene, and xylene were significantly associated with sensory irritations (e.g., eyes/nose/throat irritation) and headache (see *Table 5 (a)*). For example, when the concentration of toluene increased at the interval of 1.56 μg/m^3, the sensory irritation intensity increased by 1.12-1.17 times and the headache intensity became 1.16 times higher. And when the concentrations of xylene increased at the interval of 3.75 μg/m^3, throat and eyes irritation increased by 1.28 and 1.21 times, respectively.

Aldehydes were also found to have potential risks for passengers' health during an international flight. For example, nonanal exposure increased the odds of all sensory irritation. Odor intensity was related to elevated levels of exposure to decanal (antilog beta values = 1.25, 95% CI: 1.07 1.46). Elevated level of heptanal (antilog beta values = 1.21, 95% CI: 1.00 1.46) was also related to eyes irritation.

Table 5(b) shows that, during domestic flights, xylene exposure was also a risk factor for sensory irritation, even though the negative influences became weaker compared with those during international flights. Compared with international flights, pollutants showed an even more pronounced effect in the case of fatigue during domestic flights. With the increment concentrations of tetrachloroethylene and naphthalene at the interval of 8.18 and 6.52 μg/m^3, the intensity of fatigue increased by 1.12 and 1.08 times.

Regarding to dryness perceptions, there were no VOCs related to dryness during both international and domestic flights.

Table 5(a) Association between passengers' perceptions and exposure to volatile organic compounds in cabin environment during international flights (n=171).

	Antilog beta values (95% Confidence Interval)[a]					
	Odor intensity[a]	Nose irritation[a]	Throat irritation[a]	Eyes irritation[a]	Fatigue[a]	Headache[a]
Toluene	1.09 (0.97 1.23)	**1.17 (1.08 1.27) ****	**1.17 (1.08 1.27) ****	**1.12 (1.02 1.22) ***	1.06 (0.94 1.20)	**1.16 (1.03 1.31) ***
Ethylbenzene	1.11 (0.97 1.27)	1.30 (0.55 1.08)	**1.18 (1.08 1.29) ****	**1.12 (1.02 1.23) ***	1.08 (0.94 1.24)	**1.18 (1.03 1.36) ***
Xylene	1.00 (0.69 1.47)	1.14 (0.91 1.43)	**1.28 (1.04 1.57) ***	**1.21 (1.01 1.47) ***	0.99 (0.76 1.29)	1.08 (0.74 1.57)
Styrene	0.86 (0.49 1.49)	1.17 (0.50 1.47)	**1.35 (1.12 1.63) ****	1.15 (0.95 1.39)	1.11 (0.85 1.46)	1.01 (0.75 1.38)
Phenol	1.02 (0.96 1.09)	**1.06 (1.00 1.13) ****	**1.07 (1.02 1.13) ***	1.04 (0.99 1.08)	1.02 (0.96 1.09)	1.05 (0.99 1.12)
Hexanol-ethyl	1.08 (0.91 1.28)	1.12 (0.93 1.35)	**1.21 (1.051.40) ****	1.09 (0.96 1.25)	1.08 (0.92 1.28)	1.16 (0.97 1.39)
Heptanal	1.09 (0.75 1.59)	1.11 (0.77 1.61)	1.17 (0.87 1.56)	**1.21 (1.00 1.46) ***	0.95 (0.73 1.25)	1.25 (0.71 2.20)
Nonanal	1.15 (0.97 1.38)	**1.21 (1.03 1.41) ****	**1.22 (1.06 1.40) ****	**1.19 (1.04 1.36) ***	1.11 (0.92 1.35)	1.19 (0.99 1.44)
Decanal	**1.25 (1.07 1.46) ****	1.07 (0.92 1.25)	0.96 (0.78 1.17)	1.11 (0.94 1.32)	1.16 (0.94 1.42)	1.12 (0.89 1.41)

Table 5(b) Association between passengers' perceptions and exposure to volatile organic compounds in cabin environment during domestic flights (n=223).

	Antilog beta values (95% Confidence Interval)[a]					
	Odor intensity[a]	Nose irritation[a]	Throat irritation[a]	Eyes irritation[a]	Fatigue[a]	Headache[a]
Toluene	1.07 (0.97 1.18)	1.20 (1.00 1.45)	0.94 (0.87 1.01)	1.01 (0.98 1.03)	**1.07 (1.00 1.13) ***	1.04 (0.94 1.16)
Benzene	1.03 (0.96 1.10)	1.01 (0.95 1.07)	**0.95 (0.91 1.00) ***	1.02 (0.94 1.10)	1.02 (0.98 1.06)	1.00 (0.94 1.07)
Xylene	1.05 (0.94 1.16)	**1.12 (1.00 1.24) ***	0.99 (0.90 1.10)	1.00 (0.87 1.14)	1.06 (0.99 1.14)	1.11 (0.98 1.25)
Tetrachloroethylene	1.01 (0.91 1.13)	1.05 (0.89 1.24)	**0.87 (0.81 0.94) ****	0.99 (0.96 1.02)	**1.12 (1.02 1.23) ***	1.02 (0.92 1.14)
Naphthalene	1.09 (0.96 1.23)	**1.14 (1.01 1.29) ***	0.96 (0.85 1.09)	1.03 (0.55 1.96)	**1.08 (1.02 1.16) ***	**1.19 (1.03 1.39) ***
D-limonene	**1.12 (1.02 1.24) ***	1.10 (0.99 1.21)	1.10 (0.96 1.26)	1.00 (1.00 1.01)	0.95 (0.89 1.01)	0.95 (0.87 1.05)
Ethyl-acetate	1.06 (0.98 1.15)	**1.09 (1.01 1.17) ***	1.03 (0.96 1.11)	1.02 (0.95 1.10)	1.01 (0.96 1.07)	1.08 (0.99 1.18)

[a]Antilog beta values were estimated by IQR (Interquartile range) increase in VOCs concentrations, with adjustment for passengers' age, gender, smoking, and allergy.

* $p \leq 0.05$.

** $p \leq 0.01$.

4. Discussions

The unique aspect of this study is the concurrent measurements of cabin contaminants and environmental parameters with the administration of questionnaires to passengers on a large scale. Multivariate techniques were used to assess relationships between flight-specific VOCs concentrations and outcomes with adjustment for personal factors. The common VOCs (detection rate above 60%) in our study were benzene series (toluene, ethylbenzene, xylene, and benzene), aldehydes (formaldehyde, benzaldehyde, nonanal, hexanal, decanal, and heptanal), olefins (tetrachloroethylene, styrene, limonene), and other VOCs (hexanol_ethyl, naphthalene, phenol, dodecane, ethyl_acetate). Among them, toluene and xylene were substances associated with passengers' perceptions on both international and domestic flights. Some aldehydes (such as nonanal, heptanal, and decanal), which are potential ozone reaction by-products [38], showed a significant association with passengers' irritations on international flights.

Concentrations of detected VOCs during the cruising phase in this study were comparable to those in previous studies [39-40]. However, when the concentration levels of VOCs were analyzed and discussed separately for international flights and domestic flights, domestic flights had higher VOCs concentrations than those in international flights (see Figure 5 and Figure 6). For the cruising phase, the mean concentrations of CO_2 in domestic flights were higher than in international flights, as shown in Figure 4. Higher CO_2 concentrations mean a lower ventilation rate. And the lower ventilation rate during domestic flights may explain higher VOCs concentrations when assuming that the emission rates per person were the same on different flights. A similar situation was also found by Spengler et al. [28] that the mean concentration of VOCp (the sum of petroleum hydrocarbons) was significantly higher in flights with low ventilation rates than with high ventilation rates (p-value = 0.004). Although there were differences in concentration levels, species of VOCs detected in international and domestic flights were the same, except that heptanal and styrene were observed (DR>60%) in international flights, and ethylbenzene and dodecane (detection rate over 60%) were marked in domestic flights exclusively. This finding is consistent with Guan's study [25], which indicated that flight duration and aircraft types seldom contributed to the species of detected VOCs in cabins. Ethanol (as a typical VOC from meal serving) was less detected in our study (detection rate <60%), which is not consistent with previous studies [22]. This may be due to our restrictions on data analysis during the cruising phase (without meal serving and other specialized personnel activities). Details of VOCs exposures in different flight phases refer to Yin et al. [32].

Dryness perception was a common complaint in both international and domestic flights, as reported in previous studies. For example, the most common complaint of airline crew about CAQ (cabin air quality) was dry air (53%) in the research of Lindgren et al. [41]. But in this study, we did not find a significant association between specific VOCs and passengers' dryness perceptions. We found that dryness perceptions on passengers' noses, skins and eyes were higher during international flights, compared to those reported during domestic flights. Simultaneously, we observed the relative humidity during international flights was lower than those during domestic flights. Therefore, we suspect that passengers' dryness complaints might be due to the extremely low humidity in aircraft cabins rather than VOCs exposure.

The detected concentration of toluene xylene in our study was of the same magnitude as those observed by Crump et al.[23] and Wang et al. [21]. We found that toluene and xylene were significantly associated with sensory irritations (eyes/nose/throat） on both international and domestic flights. Headache and fatigue were associated with toluene respectively on international and domestic flights. Toluene and xylene were listed as carcinogens by IARC (International Agency for Research on Cancer) in 2017 [42]. Prolonged exposure to toluene could develop headaches[43]. This may explain the exclusively observed negative association of toluene and xylene exposure with headaches during international flights. The main route of inhalation of xylene is the respiratory system [44-47], and there are also small sections that can enter the body through skin or diet [48]. Toluene and xylene enter the body through breathing and may irritate the nasal mucosa and throat [49].

The concentration of aldehydes in our investigated aircraft cabins was in a range of 15-28 ug/m^3, which is comparable to the sum of aldehydes reported by Rosenberger[50]. However, Rosenberger did not observe an influence of high aldehyde exposure on complaints among crewmembers, which was probably due to limited sample size and short-term peak exposure. In our study, the association of some aldehydes (nonanal, decanal, and heptanal) with passengers' perceptions was also significant, especially with sensory irritations on international flights. Nonanal was found to irritate eyes [51]. And due to its semi-volatile nature, it had a long-term impact on air quality [52]. Renzettj et al. also attributed sensory irritation to high concentrations of heptanal, and nonanal [53]. In previous studies, the ozone reactions in aircraft cabins among passengers' skin, aircraft carpets, seat fabrics, and fabrics have been proven to increase the concentrations of nonanal, decanal, and heptanal [8, 54-56]. Wolkoff et al. reported that the hazard index of sensory effects for ozone-initiated reaction products and non-reactive VOCs amounted to 84% in aircraft[57]. The reactions between ozone and certain unsaturated hydrocarbons should be considered in establishing a healthy and comfortable aircraft cabins environment.

We noticed that the association of VOCs with sensory irritations was far more than with other complaints (e.g., odor irritations). Although some VOCs may reach a concentration higher than the odor thresholds, the approach to and eventual increase above the odor threshold is expected to be gradual enough for passengers to be unable to perceive the odors. The olfactory sense habituates relatively quickly. Conversely, sensory irritation (eyes, throat, nasal passages) may become more pronounced as the duration of the exposure increases [20]. The physiological effects of sensory irritations with exposure time were reflected by their more pronounced associations withtoluene, xylene, and some aldehydes in international rather than domestic flights.

The main weakness of this study is that detected compounds are constrained to those with prior knowledge of their existence. With the development of sophisticated online analytical equipment, non-targeted screening of air samples taken on aircraft should be conducted to supplement targeted studies and to identify potential chemical compounds (such as short-live radicals) and their health effects. Additionally, multiple sources on aircraft cabins determine that passengers and crew members are exposed to complex mixtures of contaminants (such as particle matter, flame retardants, tricresyl phosphates, volatile organics, and ozone) [27]. The unknown multiplicative or synergistic effects of the exposure mixture warrant further investigations.

5. Conclusions

We used a linear mixed model to analyze associations between VOCs exposure in the aircraft cabins and passengers' perceptions with adjustment for age, gender, smoking, and allergy. We found that VOCs in-cabin air could influence passengers' perceptions and SBS symptoms. Higher exposure to toluene was a risk factor for eyes irritation, headache, and fatigue among passengers. Xylene was significantly related to sensory irritations on both international and domestic flights. And aldehydes which might be generated by reaction with ozone inthe -cabin had a negative influence on irritation perceptions among passengers.

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Supplementary materials

A total of 623 passengers (i.e., 246 on international flights and 377 on Chinese domestic flights) were invited to participate in questionnaire surveys in the whole flights.

Table 1 Background information of investigated passengers in international (n=246) and domestic flights （n=377）

Variable		International fights n (%)	Domestic fights n (%)
Age [a] (years)	<21	27(11.3）	50(13.7)
	21-35	143(55.9)	197(53.5)
	36-50	59(24.6)	98(26.7)
	>50	20(8.2)	22(6.1)
Gender	female	125(51.7)	132 (35.4)
Smoke[a]	No	233(94.7)	301 (79.8)
Allergy[b]	No	206 (83.7)	297 (79.0)

[a] *Data obtained by the question of "Do you smoke?".*

[b] *Data obtained by the question of "Have you ever had an allergy?".*

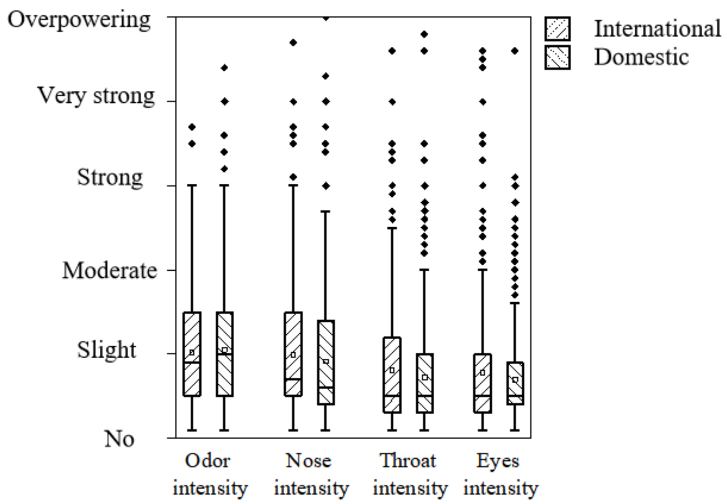

Figure 1 Evaluation of passenger odors and sensory irritation in the whole flights.

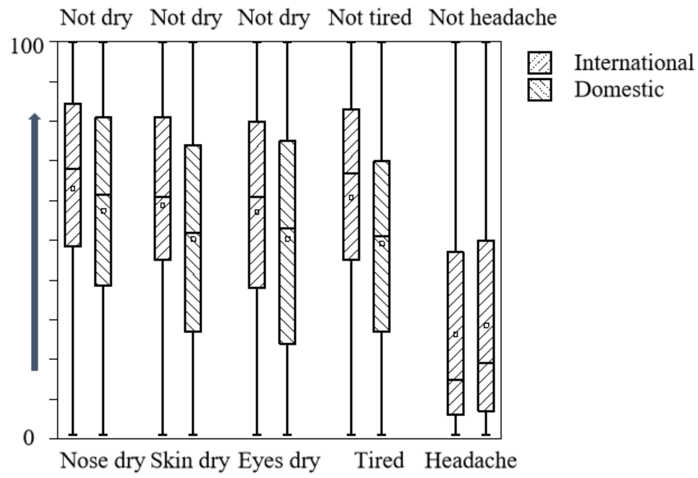

Figure 2 Evaluation of dryness perceptions, fatigue and headache in the whole flights.