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Associations of indoor carbon dioxide concentrations, air temperature and humidity with perceived air quality and sick building syndrome symptoms in Chinese homes

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Practical implications

The findings of this study indicate the importance of indoor air humidity on perceived indoor air quality and SBS symptoms. We found a high indoor CO_2 concentration weakened the benefit of high humidity for skin SBS symptoms. Ventilation and humidity should be both considered in creating a proper home environment.

Abstract

The indoor environment is important for occupants' health. From March 1st, 2018 to February 28th, 2019, we continuously monitored indoor temperature (T), relative humidity (RH) and CO_2 concentration in bedrooms via an online system in 165 residences that covered all five climate zones of China. Meanwhile, we asked one specific occupant in each home to complete questionnaires about perceived air quality and sick building syndrome (SBS) symptoms at the end of each month. Higher CO_2 concentration was significantly associated with a higher percentage of perceived stuffy odor and skin SBS symptoms. Higher relative humidity was associated with higher percentage of perceived moldy odor and humid air, while lower RH was associated with a higher percentage of perceived dry air. Occupants who lived in residences with high RH were less likely to have mucosal and skin SBS symptoms (adjusted odds ratio (AOR): 0.73-0.78). However, the benefit of high humidity for perceived dry air and skin dryness symptoms would likely be weaker if there is a high CO_2 concentration level.

Keywords Sick building syndrome; Home; CO_2; Odors; Relative humidity; Perceived dry air

1 Introduction

Since the 1970s, building construction has utilized energy conservation measures such as reduced air exchange that commonly led to building-associated illness. In China, air change rates in residential buildings are generally low, especially in the north.[1,2] Low air change rates mean high concentrations of indoor generated pollutants. Indoor pollutants, for example, bioaerosols, volatile organic compounds and molds, are associated with increased risk of a suite of symptoms called sick building syndrome (SBS)[3-6]. Since WHO first reported on SBS in 1983,[5] a large number of SBS studies have been conducted to investigate SBS symptoms and their relationships with indoor environmental factors.[7-10] Since people spend most of their time at home,[11-13] the influence of the home environment on SBS should be further investigated. In China, several studies of SBS have recently been performed.[4,14-17] The CCHH (China, Children, Homes, Health) study in Tianjin (a city in northeast China) reported that 14% of parents have weekly general symptoms and 11% and 9% have weekly mucosal symptoms and skin symptoms, respectively.[18] The prevalences of weekly general symptoms, mucosal symptoms and skin symptoms were 4.2-14.6%, 3.2-4.8% and 4.3%, respectively, in Changsha (a city in central China) from the same study (CCHH study);[16] and 13.5%, 8.5% and 5.2%, respectively, in Chongqing (a city in southwest China).[14] Differences in home environments and climate among different areas in China are related to differences in prevalence of SBS. However, few studies on national investigation of home environmental-related SBS symptoms exist.

Compared with evoking SBS symptoms, odors of some indoor pollutants can often be detected at lower concentrations.[19,20] Therefore, perception of odors is the primary discriminant of indoor air quality and is often used to evaluate the acceptability of indoor air.[14,21,22] Moreover, perception of odors is associated with occupants' health problems.[4,14,15,23,24] In homes, odors are mainly from human bio-effluents, environmental tobacco smoke (ETS), bio-odorants released from fungus or mold, perfume and cosmetics, and volatile building materials.[19,25] Air humidity and temperature influence the emission characteristics of building materials and affect the immediate and longer-term perceived odor.[26,27] Fang et al.[26] found the air was perceived as less acceptable with increasing temperature and humidity. However, the issue is complex because both the air temperature and humidity and pollutant emission influence the perception of odor.

Indoor air humidity is important with respect to health[22] but the association between perceived humidity and air humidity is not clear because there are no specific sensory receptors for humidity.[28] In contrast, dryness has often been perceived in the presence of dampness indicators.[29.30] Studies have found that an increased air pollution level was a more important factor for perceived ‘‘dryness’’ than low relative air humidity.[31,32]

Indoor environmental exposure level in residential buildings is uncertain because in addition to indoor sourced pollutants it depends on outdoor conditions and the behavior of building occupants.[33] Both indoor pollutants and outdoor conditions change over time.[34.35] However, most studies of indoor environmental exposures used instantaneous measurements,[36] which may not be able to capture and represent the true variability and may not be representative of actual exposures. A consecutive survey accompanied by air quality measurements in real indoor space must be performed to characterize the changes in air quality parameters and the prevalence of SBS.

The present study aimed to investigate 1) the relationship of CO_2 concentration, temperature, humidity with perceived odors and 2) the effect of CO_2 concentration, temperature, humidity on SBS symptoms with long-term (one year) measurements in Chinese residences in five climate zones.

2 Methods

This study was conducted between March 1, 2018 and February 28, 2019. It was part of a national investigation of ventilation in residences.[1,37,38] We continuously monitored indoor temperature (T), relative humidity (RH) and carbon dioxide in bedrooms for one complete year using an online system in 165 residences in 11 representative provinces/municipalities. These provinces/municipalities cover all five climate zones, as shown in Figure 1. Table S1 in the supplementary information shows the climatic characteristics of each of the five climate zones.[39] The sample size for each zone was roughly proportional to the number of families in the zone.[40]

In this study, indoor temperature, the relative humidity and carbon dioxide were monitored and recorded every minute using an Ikair environmental monitoring kit, which has measurement ranges of -40-125 °C for the air temperature, 0-100% for the relative humidity and 400-10000 ppm for carbon dioxide. The measurement accuracies for the parameters were ±0.3 °C, ±3% and 70 ppm or ±3% of reading respectively.

Occupants reported perceived odors and humidity, SBS symptoms and personal demographic information through responses to questionnaires.

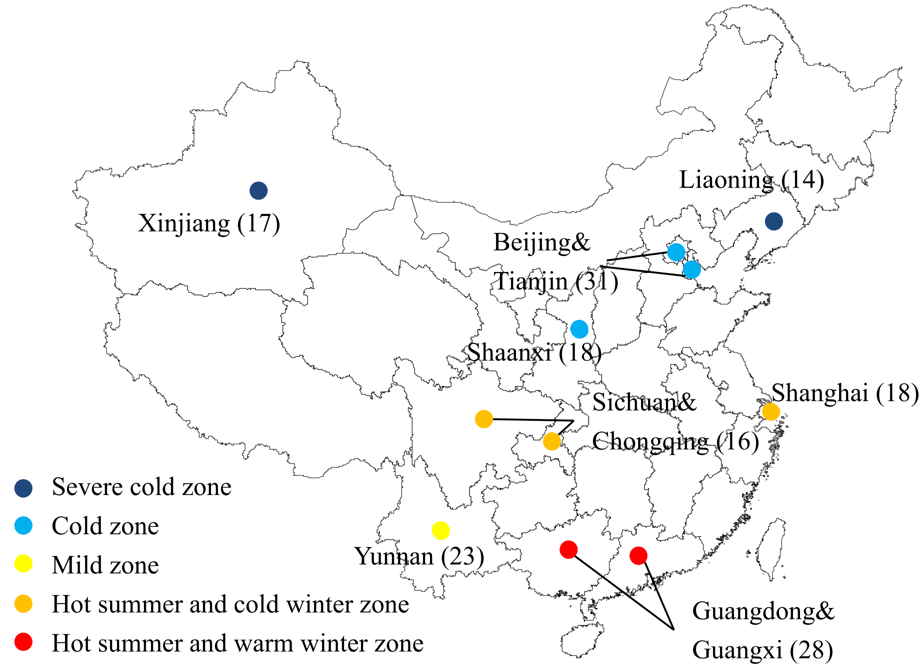

Fig.1 Sample locations and number of participants in each zone

2.1 Questionnaires

In each month during the investigation period (March 2018-February 2019), a questionnaire was administrated to one reference person in the household. This individual was asked to answer questions about the responder's experience in the previous month. Supplementary Document "Questionnaire" shows the complete questionnaire.

Questions about SBS symptoms comprised three groups: general SBS symptoms (fatigue, heavy head, headache, dizziness, difficulty concentrating), mucosal SBS symptoms (eye irritation, nose irritation, dry throat, cough), and skin SBS symptoms (dry facial skin, dry ears, dry hands). Each question had three possible responses: (1) Yes, often (every week); (2) Yes, sometimes; (3) No, never.

Questions about perceived indoor air qualities were about perceived odor and humidity. They were: "Have you during the last month been bothered by any of the following odors in your residence: (1) stuffy odor, (2) unpleasant odor, (3) moldy odor, (4) tobacco smoke, (5) dry air, (6) humid air?" For each, there were three options for the response (1) Often; (2) Sometimes; (3) Never.

2.2 Statistical analysis

Daily mean temperature and relative humidity were calculated and involved in data analysis. While CO_2 concentration between 0:00 am to 7:00 am (when homes were occupied) was summarized to indicate indoor potential sources (i.e., occupants) and ventilation rate.

In the analysis, answers on SBS symptoms and perceived indoor air quality were classified into two categories ("No, never", "Yes, often or sometimes").

The statistical analyses were performed using STATA 14.0. Odds ratios of indoor physical parameters for perceived indoor air qualities and SBS symptoms were

calculated in three-level (climate zone, individual, and time-serial) logistic regression models with adjustment for gender, age, allergic history and current smoker. Indoor physical parameters were examined as both a continuous and a categorical variable. The results are shown as adjusted odds ratios (AORs) with 95% confidence intervals (CIs). We accepted *P*-values < 0.05 as statistically significant.
The Research Office at Tianjin University granted ethical approval for this study.

3 Results

A total of 1285 questionnaires from 165 residences in 12 months were returned. The response rate was 64.9% with small fluctuations across five climate zones. Table 1 shows demographic information. Fig. 2 and Supplementary Table S2 summarize the proportions of SBS symptoms among participating occupants. The percentage of general SBS symptoms was the highest (74.0%), followed by mucosal SBS symptom (65.8%). The highest percentage of general SBS symptom was reported in the cold zone (78.5%), followed by the severe cold zone (76.2%). The highest percentage of mucosal SBS symptoms and skin SBS symptoms were both reported for the severe cold zone (mucosal SBS: 71.4%; skin SBS: 51.6%). Fig. 3 and Supplementary Table S3 show the proportions of perceived odor and humidity. The most frequently perceived odor was dry air (47.4%), followed by stuffy odor (46.1%). Supplementary Fig. S2 shows the proportions of perceived odor and humidity in each climate zone. The highest percentages of stuffy odor and unpleasant odor were both reported in the cold zone (stuffy odor: 58.0%; unpleasant odor: 37.5%). The highest percentage of perceived dry air was reported in the mild zone (63.2%), followed by the severe cold zone (59.1%) and the cold zone (54.4%). The zones with hot summers reported a higher percentage of perceived humid air (HSWW: 38.4%; HSCW: 35.5%).

Table 1 Demographic information for participating occupants (n =165).

Items	n (%)
Age	
20-29	28(17.0)
30-39	78(47.3)
40-49	31(18.8)
50-59	25(15.1)
60-69	2(1.2)
No information	1(0.6)
Gender	
Male	72(43.6)
Female	93(56.4)
Allergic history	
Yes	60(36.4)
No	105(63.6)
Current smoker	
Yes	21(12.7)
No	144(87.3)

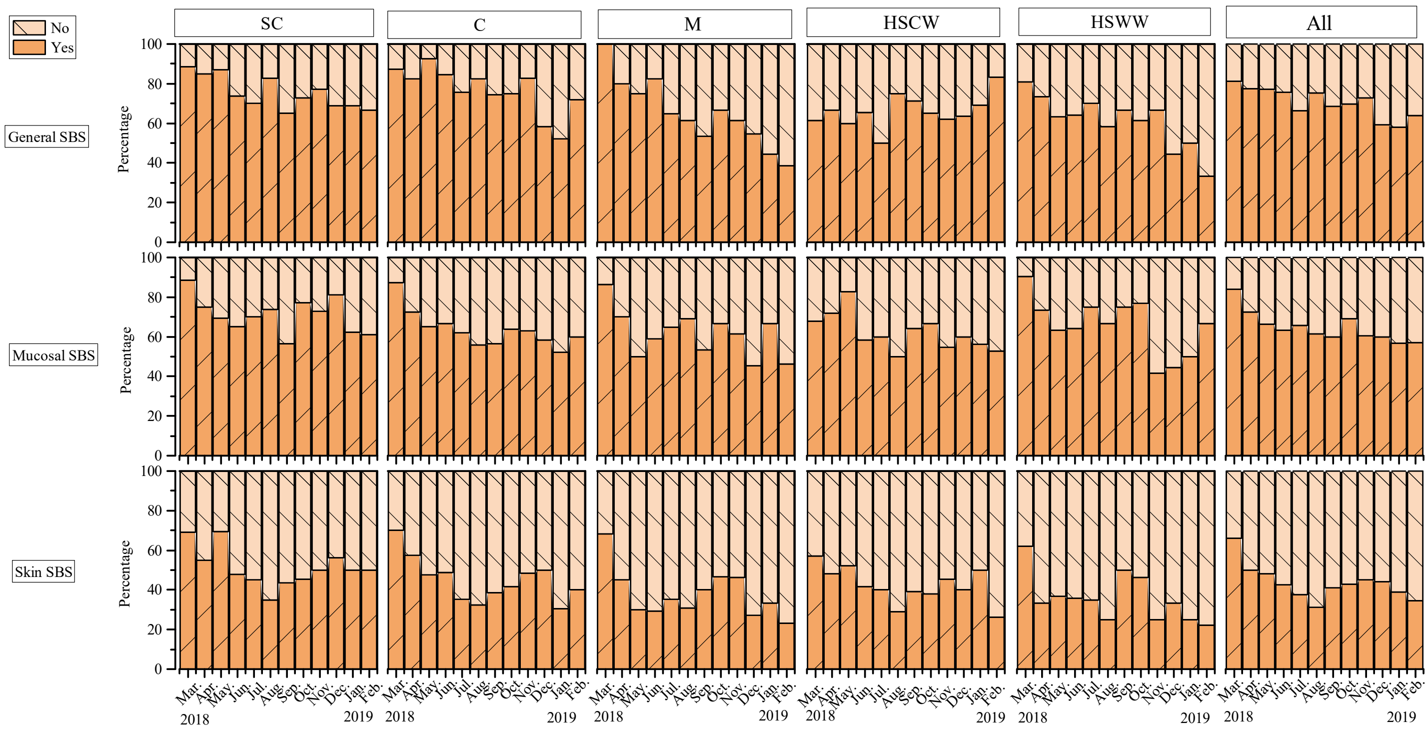

Fig. 2 Proportions of sick building syndrome (SBS) symptoms in each month among all the participating occupants. (General SBS: at least one general SBS symptom e.g. fatigue, heavy head, headache, dizziness, concentration difficulty. Mucosal SBS: at least one mucosal SBS symptom e.g. eye irritation, nose irritation, throat hoarse, cough. Skin SBS: at least one skin SBS symptom e.g. dry facial skin, itchy ears, dry hands. SC: severe cold zone; C: cold zone; M; mild zone; HSCW: hot summer and cold winter zone; HSWW: hot summer and warm winter.)

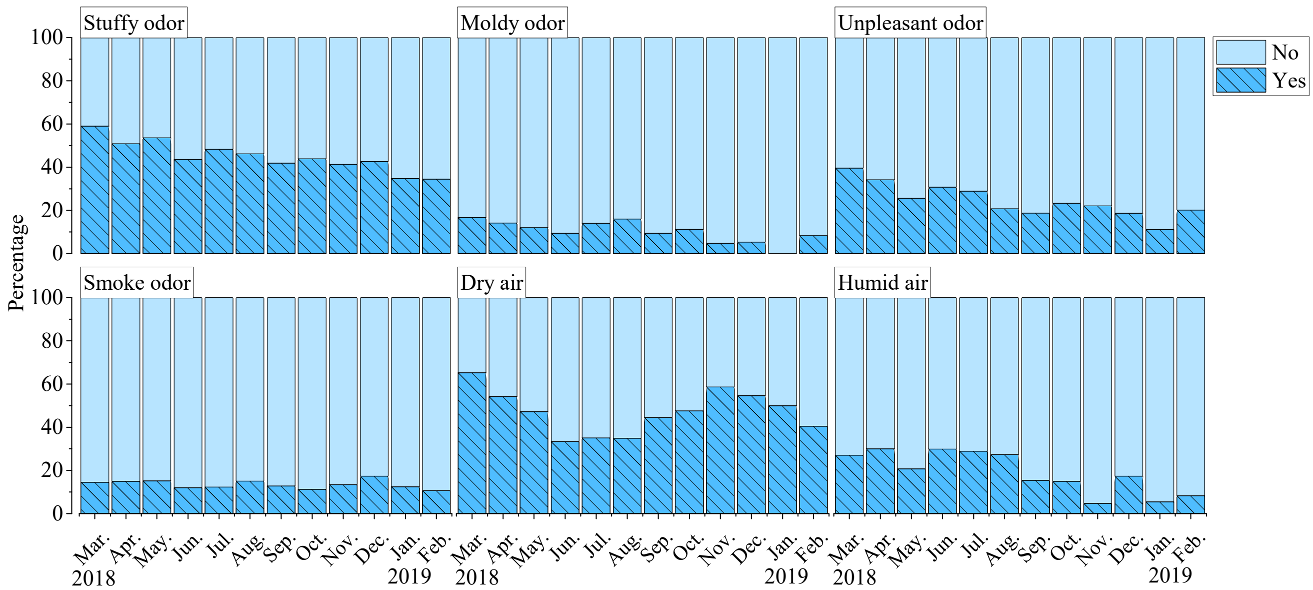

Fig. 3 Proportions of perceived odor and humidity in each month among all the participating occupants.

In the participating homes, median value of CO_2, T and RH were 813 ppm, 25.6 ºC and 46.7%, respectively. Indoor temperature in each climate zone trended with outdoor temperature (Supplementary Table S1). However, indoor temperatures in northern China (severe cold zone and cold zone) (median: 23.5-26.1 ºC) were higher than in southern China (median: 16.8-27.2 ºC) during heating season (November to March) (Fig. 4), due to district heating systems used in northern China. The mild zone had relatively constant and mild indoor temperatures (median: 17.3-27.4 ºC). The CO_2 concentration in the mild zone was also relatively constant and low (median: 552-767 ppm). In the severe cold and the cold climate zones, CO_2 concentration was high in winter (median: 914-1141 ppm) and low in summer (median: 610-891 ppm). It is interesting to find that in the south China with hot summer zone, CO_2 concentration was also high in summer (median: 773-1159 ppm). This may be due to occupants' use of air conditioning. Median RH varied from 22.2-61.6% in the five climate zones (Fig. 4). The hot summer and warm winter zone had the highest RH (51.9-61.6%) and the severe cold zone had the lowest RH (22.2-43.9%). RH in the severe cold zone, the cold zone and the mild zone changed with the seasons, i.e., it was higher in summer and lower in winter.

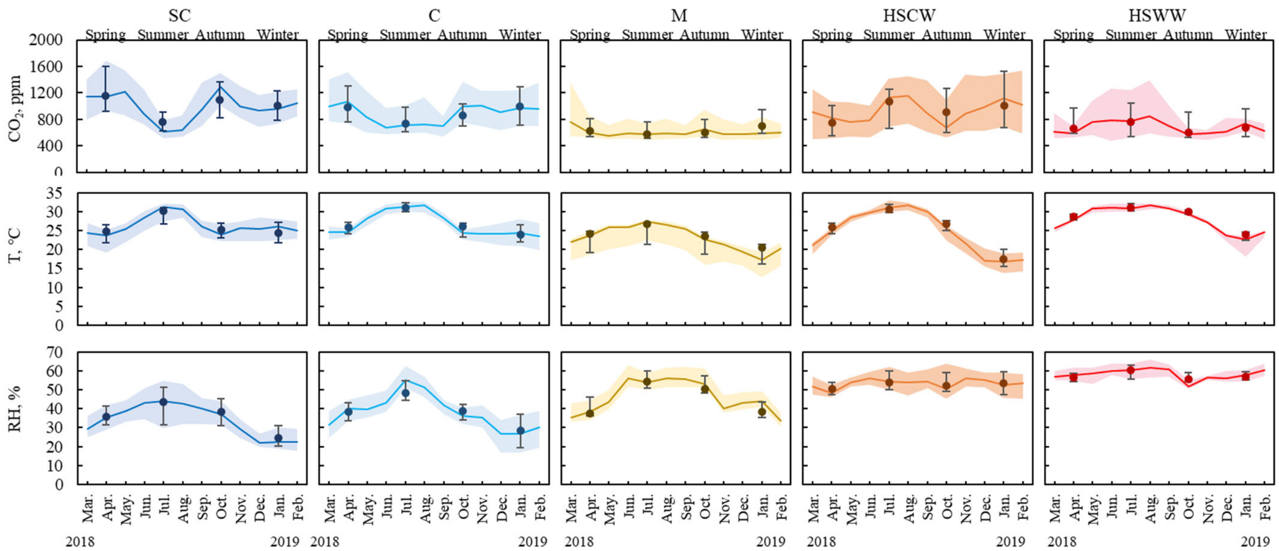

Fig.4 Monthly and seasonal average CO_2 concentration (0:00-7:00), indoor temperature (T, 24 hours) and related humidity (RH, 24 hours) in 165 Chinese homes (SC: severe cold zone, N=31; C: cold zone, N=49; M; mild zone, N=23; HSCW: hot summer and cold winter zone, N=34; HSWW: hot summer and warm winter, N=28. The lines are median values of monthly average values in homes and the colored regions represent the interquartile range of monthly average values in homes. The dots are median values of seasonal average values in homes and the error bars represent the interquartile range of seasonal average values in homes)

Table 2 shows the associations of SBS symptoms with age, gender, current smoker and allergic history. "Older" was a risk factor for general SBS symptoms. Allergic history was significantly associated with increases in SBS symptoms. Table 3 shows the associations of perceived odor and humidity with age, gender, current smoker and allergic history. Female gender was significantly associated with higher perceived stuffy odor.

Table 2 Odds ratios (95% confidence interval)[a] of personal variables for sick building syndrome (SBS) symptoms in three-level (climate zone-individual-time serial) logistic regression analyses (n=1285)

	One general SBS symptom[b]	One mucosal SBS symptom[c]	One skin SBS symptom[d]
Gender[e]	2.15(0.93,4.93)	0.79(0.38,1.66)	1.39(0.67,2.88)
Age[f]	**1.60(1.04,2.46)**[*]	1.30(0.90,1.89)	1.37(0.95,1.97)
Allergic history[g]	1.43(0.85,2.39)	**3.66(2.21,6.05)**[***]	**3.51(2.17,5.66)**[***]
Current smoker[h]	0.52(0.21,1.24)	1.61(0.67,3.88)	0.44(0.18,1.09)

[a]***: $P<0.001$, **: $P<0.01$, *: $P<0.05$.

[b]At least one general SBS symptom e.g. fatigue, heavy head, headache, dizziness, concentration difficulty: yes (often/sometimes) vs. none.

[c]At least one mucosal SBS symptom e.g. eye irritation, nose irritation, throat hoarse, cough: yes

(often/sometimes) vs. none.

[d]At least one skin SBS symptom e.g. dry facial skin, itchy ears, dry hands: yes (often/sometimes) vs. none.

[e]Male (reference) vs. female.

[f]Age was divided into five groups: 20-29 years old, 30-39 years old, 40-49 years old, 50-59 years old and 60-69 years old.

[g]No allergic history (reference) vs. allergic history.

[h]Non-current smoker vs. current smoker.

Table 3 Odds ratios (95% confidence interval)[a] of personal variables for perceived odor and humidity in three-level (climate zone-individual-time serial) logistic regression analyses (n=1285)

	Stuffy odor	Moldy odor	Unpleasant odor	Dry air	Humid air
Gender[b]	**2.36(1.16,4.79)** *	0.49(0.18,1.33)	**2.16(1.02,4.57)** *	1.51(0.90,2.52)	1.15(0.67,1.97)
Age[c]	0.96(0.66,1.39)	0.67(0.40,1.13)	0.90(0.62,1.31)	1.09(0.84,1.42)	1.13(0.85,1.49)
Allergic history[d]	1.10(0.69,1.76)	0.88(0.43,1.78)	1.31(0.79,2.19)	1.19(0.81,1.76)	1.00(0.64,1.56)
Current smoker[e]	0.55(0.22,1.36)	0.63(0.16,2.57)	0.35(0.12,1.05)	0.70(0.34,1.43)	0.62(0.28,1.39)

[a]***: $P<0.001$, **: $P<0.01$, *: $P<0.05$.

[b]Male (reference) vs. female.

[c]Age was divided into five groups: 20-29 years old, 30-39 years old, 40-49 years old, 50-59 years old and 60-69 years old.

[d]No allergic history (reference) vs. allergic history.

[e]Non-current smoker vs. current smoker.

Table 4 shows associations of perceived odor and humidity with indoor T, RH and CO_2 concentration, calculated by logistic regression models. Higher CO_2 concentration was significantly associated with higher perceived stuffy odor. Higher RH was significantly associated with perceived moldy odor and humid air. Lower RH was significantly associated with perceived dry air. There was a clear dose-response relationship between CO_2 concentration and stuffy odor, as well as between RH and perceived dry/humid air (Table 5).. It is interesting to find that in rooms with high CO_2 concentration, the AOR of RH for perceived dry air was higher than in low CO_2 rooms (Fig. 5), which means the protective effect of higher RH was weaker in high level CO_2 concentration rooms.

Table 4 Adjusted odds ratios (95% confidence interval)[a] for monthly CO_2 (0:00-7:00), temperature (T, 24 hours) and relative humidity (RH, 24 hours) for perceived odor and humidity in three-level (climate zone-individual-time serial) logistic regression analyses (n=1143[b])

	Stuffy odor	Moldy odor	Unpleasant odor	Dry air	Humid air
CO_2 (per 100 ppm)	**1.08(1.04,1.13)** ***	0.96(0.90,1.02)	1.03(0.98,1.07)	1.04(1.00,1.08)	0.95(0.91,1.00)
T (per 1 ^oC)	1.02(0.99,1.06)	1.05(0.99,1.11)	0.98(0.94,1.02)	0.97(0.94,1.01)	**1.08(1.04,1.12)** ***

RH (per 10%)	0.92(0.78,1.09)	**1.35(1.02,1.79)** *	0.92(0.77,1.10)	**0.51(0.43,0.61)** ***	**1.57(1.28,1.92)** ***

[a]Adjusted for age, gender, allergic history and current smoker. ***: P<0.001, **: P<0.01, *: P<0.05.[b]Subjects with missing data on CO_2, T and RH (n=142) were excluded.

Table 5 Adjusted odds ratios (95% confidence interval)[a] for CO_2 (average during 0:00-7:00), temperature (T, 24 hours) and relative humidity (RH, 24 hours) with inter-quartile values for perceived odor and humidity in three-level (climate zone-individual- time serial) logistic regression analyses (n=1143[b])

	Stuffy odor	Moldy odor	Unpleasant odor	Dry air	Humid air
CO_2					
1st quartile (438-587 ppm)	1	1	1	1	1
2nd quartile (587-813 ppm)	1.42(0.81,2.48)	1.20(0.52,2.75)	1.56(0.83,2.92)	0.77(0.46,1.31)	0.73(0.42,1.27)
3rd quartile (813-1200 ppm)	**2.10(1.11,3.98)** *	0.93(0.33,2.60)	1.99(0.96,4.14)	0.90(0.53,1.54)	0.94(0.55,1.61)
4th quartile (1200-3904 ppm)	**3.00(1.54,5.85)** **	0.55(0.17,1.78)	1.78(0.82,3.86)	0.96(0.52,1.76)	0.50(0.25,1.00)
T					
1st quartile (7.1-21.7 ºC)	1	1	1	1	1
2nd quartile (21.7-25.6 ºC)	1.68(0.90,3.10)	1.46(0.53,3.96)	0.96(0.51,1.80)	**2.05(1.23,3.41)** **	1.53(0.77,3.02)
3rd quartile (25.6-28.9 ºC)	1.66(0.93,2.96)	1.79(0.72,4.47)	0.77(0.41,1.47)	1.52(0.86,2.71)	**1.88(1.00,3.54)** *
4th quartile (28.9-37.2 ºC)	1.69(0.80,3.46)	1.52(0.58,3.96)	0.63(0.30,1.33)	1.00(0.56,1.79)	1.80(0.96,3.38)
RH					
1st quartile (10.9-35.2%)	1	1	1	1	1
2nd quartile (35.2-46.7%)	0.87(0.51,1.50)	1.26(0.46,3.43)	1.36(0.79,2.35)	**0.47(0.28,0.80)** **	**2.14(1.06,4.35)** *
3rd quartile (46.7-55.3%)	0.85(0.44,1.65)	2.60(0.78,8.66)	0.61(0.30,1,23)	**0.13(0.06,0.27)** ***	**5.83(2.44,13.94)** ***
4th quartile (55.3-80.4%)	0.84(0.35,2.00)	**5.05(1.17,21.88)** *	0.82(0.32,2.10)	**0.11(0.05,0.21)** ***	**9.00(3.90,20.78)** ***

[a]Adjusted for age, gender, allergic history and current smoker. ***: P<0.001, **: P<0.01, *: P<0.05.

[b]Subjects with missing data on CO_2, T and RH (n=142) were excluded.

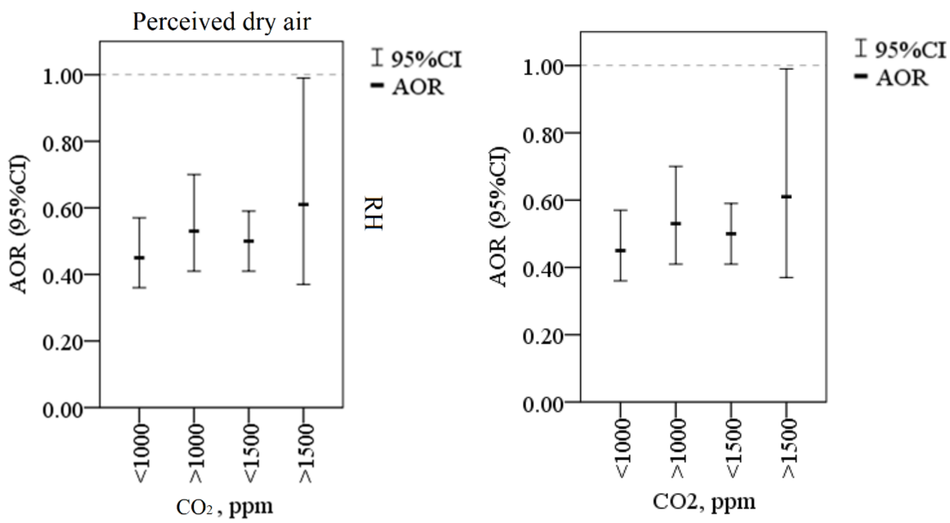

Fig.5 Adjusted odds ratios of relative humidity (RH) for perceived dry air in three-level (climate zone-individual-time serial) logistic regression analyses in two CO_2 concentration ranges (adjusted for age, gender, allergic history and current smoker)

Table 6 shows associations of SBS symptoms with indoor T, RH and CO_2 concentration. CO_2 concentration was associated with increased general SBS and skin SBS symptoms, but not significantly. Higher RH was significantly associated with reduced mucosal SBS symptoms and skin SBS symptoms. Table 7 shows adjusted odds ratios of T, RH and CO_2 concentration with inter-quartile values for SBS symptoms. Adjusted odds ratios of mucosal SBS symptoms and skin SBS symptoms were lower for higher RH. In the rooms with high CO_2 concentration, the AORs of RH for general and skin SBS symptoms was higher than in low CO_2 rooms (Fig. 6), which means the protective effect of higher RH was stronger in low level CO_2 concentration rooms.

Table 6 Adjusted odds ratios (95% confidence interval)[a] of CO_2 (average during 0:00-7:00), temperature (T, 24 hours) and relative humidity (RH, 24 hours) for sick building syndrome (SBS) symptoms in three-level (climate zone-individual-time serial) logistic regression analyses (n=1143[b])

	One general SBS symptom[c]	One mucosal SBS symptom[d]	One skin SBS symptom[e]
CO_2 (per 100 ppm)	1.02(0.97,1.07)	1.00(0.96,1.04)	1.03(0.99,1.08)
T (per 1 ºC)	1.03(0.99,1.07)	0.99(0.95,1.03)	**0.94(0.90,0.98)****
RH (per 10%)	0.96(0.80,1.14)	**0.78(0.65,0.93)** **	**0.73(0.62,0.87)** ***

[a]Adjusted for age, gender, allergic history and current smoker. ****P*<0.001, ***P*<0.01, **P*<0.05.
[b]Subjects with missing data on CO_2, T and RH (n=142) were excluded.
[c]At least one general SBS symptom e.g. fatigue, heavy head, headache, dizziness, concentration difficulty: yes (often/sometimes) vs. none.
[d]At least one mucosal SBS symptom e.g. eye irritation, nose irritation, throat hoarse, cough: yes (often/sometimes) vs. none.
[e]At least one skin SBS symptom e.g. dry facial skin, itchy ears, dry hands: yes (often/sometimes)

vs. none.

Table 7 Adjusted odds ratios (95% confidence interval)[a] of CO_2 (average during 0:00-7:00), temperature (T, 24 hours) and relative humidity (RH, 24 hours) with inter-quartile values for sick building syndrome (SBS) symptoms in three-level (climate zone-individual-time serial) logistic regression analyses (n=1143[b])

	One general SBS symptom[c]	One mucosal SBS symptom[d]	One skin SBS symptom[e]
CO_2			
1st quartile (438-587 ppm)	1	1	1
2nd quartile (587-813 ppm)	1.41(0.74,2.69)	0.78(0.42,1.43)	1.78(0.96,3.29)
3rd quartile (813-1200 ppm)	0.66(0.30,1.43)	1.12(0.58,2.16)	**2.71(1.16,6.35)***
4th quartile (1200-3904 ppm)	0.97(0.43,2.18)	0.94(0.44,2.01)	1.58(0.77,3.25)
T			
1st quartile (7.1-21.7 ºC)	1	1	1
2nd quartile (21.7-25.6 ºC)	1.66(0.94,2.92)	1.11(0.59,2.09)	0.90(0.52,1.57)
3rd quartile (25.6-28.9 ºC)	1.98(0.96,4.09)	0.80(0.42,1.54)	0.58(0.29,1.18)
4th quartile (28.9-37.2 ºC)	1.20(0.61,2.33)	1.10(0.57,2.10)	0.53(0.27,1.01)
RH			
1st quartile (10.9-35.2%)	1	1	1
2nd quartile (35.2-46.7%)	1.19(0.66,2.13)	0.66(0.36,1.21)	0.84(0.50,1.42)
3rd quartile (46.7-55.3%)	0.95(0.51,1.77)	**0.36(0.18,0.70)****	**0.36(0.19,0.69)****
4th quartile (55.3-80.4%)	0.74(0.35,1.58)	0.53(0.22,1.27)	0.48(0.23,1.01)

[a]Adjusted for age, gender, allergic history and current smoker. ****P*<0.001, ***P*<0.01, **P*<0.05.

[b]Subjects with missing data on CO_2, T and RH (n=142) were excluded.

[c]At least one general SBS symptom e.g. fatigue, heavy head, headache, dizziness, concentration difficulty: yes (often/sometimes) vs. none.

[d]At least one mucosal SBS symptom e.g. eye irritation, nose irritation, throat hoarse, cough: yes (often/sometimes) vs. none.

[e]At least one skin SBS symptom e.g. dry facial skin, itchy ears, dry hands: yes (often/sometimes) vs. none.

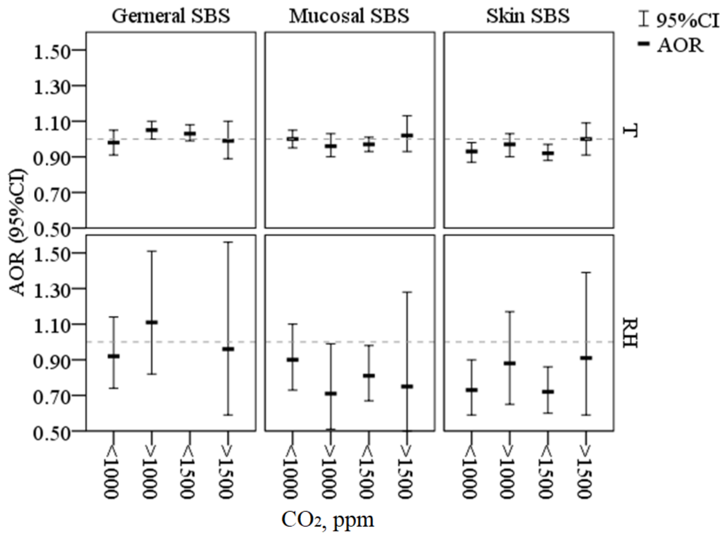

Fig.6 Adjusted odds ratios of temperature (T, 24 hours), relative humidity (RH, 24 hours) for sick building syndrome (SBS) symptoms in three-level (climate zone-individual-time serial) logistic regression analyses in two CO_2 concentration ranges (adjusted for age, gender, allergic history and current smoker)

4. Discussion

This survey was conducted in all five of China's climates zones. In this study, indoor environment was subjectively and objectively evaluated by questionnaire and long-term (1-year) real time monitoring in the surveyed homes. We found associations between indoor environmental factors and SBS.

General SBS symptoms were the most prevalent, followed by mucosal SBS symptoms. Skin SBS symptoms were the least prevalent. These are consistent with other Chinese studies, for example, in Tianjin,[4,18] and in Chongqing.[14]

Occupants with allergic history reported more SBS symptoms. Norbäck and Edling[41] found that subjects who were prone to infections reported more SBS symptoms. In other studies, both a history of allergic disorder and a history of atopy have been shown to be risk factors for SBS symptoms.[42-45] This is likely because an SBS symptom can be caused by different mechanisms, including airway infections, inflammations and allergic reactions.[46] With regards to perceived odor and humidity, more reports by occupants with a history of asthma, rhinitis and eczema suggest that symptomatic people may be more sensitive to the indoor environment and/or more prone to report poor indoor environment.[47]

Our results demonstrated associations between perceived and measured indoor air quality. Perceived stuffy odor was associated with higher CO_2 concentration. Perceived moldy odor and humid air were associated with higher RH, while perceived dry air was associated with low RH.. There have been different views about perceived "dry air". Some intervention studies have shown that an increase of RH may alleviate the perceived dry air.[48-50] Others, however, have shown that perceived dry air is not necessarily associated with the actual air humidity.[51] Instead, perceived dry air can indicate the presence of air pollutants.[52] It has been suggested that air pollution is a more important determining factor for the sensation of dryness than low RH.[7,27] In our study, perceived dry air was associated with higher CO_2 concentration. In addition, the protective effect of higher RH on perceived dry air was weaker in rooms with high CO_2 concentration. This observation suggests a modifying effect of CO_2 concentration, a proxy for ventilation,[53] for the relation of RH to perceived dry air. This may be because a lack of ventilation increases air pollution, which in turn decreases the ability of high RH to decrease perceived dry air.

In this study, we found RH was a significant risk factor for SBS symptoms, especially for mucosal SBS symptoms and skin SBS symptoms. Different air humidity will alter mucous viscosity and mucociliary activity.[54] Mucosal function depends strongly on the humidity and heat of the inhaled air.[54] Exposure to low RH aggravates eye tear film stability, resulting in desiccation, hyperosmolarity and inflammatory reactions in the eye.[55] Studies of epidemiology, clinical studies, and experiments on human exposure have indicated that low RH plays an important role in the increase of SBS symptoms.[56,57] Increase of bedroom RH has been proposed to have a beneficial effect.[58] However, high RH may increase the emission of volatile organic compounds (VOCs) from building materials.[59-63] Moreover, in indoor environments with high humidity, the presence of mold and house dust mites is higher.[64] The protection of high RH for mucosal SBS symptoms in our study may be because concentrations of VOCs in residential environments, in general, are orders of magnitude below thresholds for sensory irritation in the eyes and airways, from a toxicological point of view.[65] Our findings support both the effect of indoor humidity on SBS symptoms, as well as the effect of indoor pollutants. In a room with high CO_2 concentration, which indicted a more pollutant indoor environment, the benefits of high RH for skin SBS symptoms are less (See Fig. 6). Unfortunately, indoor pollutants, for example, formaldehyde, VOCs, particulate matter, were not measured simultaneously with these physical parameters (such as RH and CO_2 concentrations). Further sophisticated studies are needed to elucidate the combined effects of RH and CO_2 on SBS symptoms.

Previous studies suggest that the risk of SBS continued to decrease with CO_2 decreasing below 800 ppm in offices and schools.[66] However, in this study, high CO_2 concentration is not a very strong risk factor for SBS except for skin symptoms. CO_2 in residences is mainly generated by human beings and related to the number of occupants. By itself, CO_2 does not have deleterious effects on occupants under typical indoor exposure levels.[68] But as a metabolic product, CO_2 is a proxy for pollutants generated by occupants, so it is not surprising to find associations between CO_2 and odors in this study. In the history of indoor air studies, CO_2 has been used as an indicator for indoor air quality.[69] CO_2 produced by occupants may not be removed efficiently if ventilation rate is low. Therefore, it has been called as a proxy for ventilation. However, the home environment is characterized by low occupancy levels (compared to offices and schools). Building materials and furnishings may be another nonnegligible pollution source in homes and can have substantial influence on occupants' health. Especially in present China, with the development of urbanization and modernization, more and more new chemical consumer products are used in modern homes. Under such circumstance, CO_2 concentration may be not a comprehensive indicator of indoor air quality in homes.

Strengths and Limitations

A strength of this study is that our data covered all climate zones in China, for all seasons. Variable indoor physical parameters resulting from a range of outdoor RH and T in all seasons and climate zones broadened the study and increased the possibility of combining indoor physical parameters. Moreover, a full year's measurement is longer than previous studies. That each self-report on SBS symptoms corresponding to simultaneous measurements allowed us to not be confounded by seasonal variations of measured or perceived indoor air quality.

A limitation of our study is possible selection bias and recall bias. A relatively small number of subjects in each climate zones were included in this study, which could have biased the selection of participants. The percentage of SBS in each climate zone may be not representative. But considering the whole of China in this study, we have no *prior* information on occupants' health status, and the sample size of this study was large with a good response rate (64.9%), so selection bias is unlikely. The short (one month) recall period can preclude recall bias in which occupants may overestimate or underestimate their SBS symptoms or perceived indoor air quality. In addition, as a number of statistical tests were performed, significance levels were high ($p<0.05$) for the SBS symptoms. Thus, seriously biased by selection/recall or by chance findings most likely cannot explain the strong association. The second limitation is that we did not consider outdoor seasonal pollutants such as pollen and ozone. Associations between CO_2/T/RH with perceived air quality and SBS symptoms might be confounded by these exposures. The third limitation is that readings of monitors may drift during the one year of measurement. The lower limit of CO_2 sensor drifted from original -3% to -10%. Hou et al. detailed the calibration methods and results.[1]

5 Conclusion

This study evaluated subjectively and objectively indoor environment in all five of China's climates zones based on a one-year continuously monitoring campaign and monthly-repeated questionnaire survey.

CO_2 concentration were positively associated with percentage of perceived stuffy odor. Occupants who lived in residences with low CO_2 concentration were less likely to have skin SBS symptoms.

RH was positively associated with percentage of perceived moldy odor and humid air, and negatively associated with perceived dry air. Increasing indoor air humidity to a reasonable level alleviated mucosal SBS symptoms and skin SBS symptoms. However, the benefit of high humidity for perceived dry air and skin dryness symptoms was weaker under high CO_2 concentration level.

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