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INDOOR HUMIDITY LEVELS AND ASSOCIATIONS WITH REPORTED SYMPTOMS IN OFFICE BUILDINGS

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Abstract

Moderate indoor relative humidity (RH) levels (i.e., 40%–60%) may minimize transmission and viability of some viruses, maximize human immune function, and minimize health risks from mold, yet uncertainties exist about typical RH levels in offices globally and about the potential independent impacts of RH levels on workers' health. To examine this, we leveraged one year of indoor RH measurements (which study participants could view in real time) in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom, and the United States, and corresponding self-report symptom data from 227 office workers in a subset of 32 buildings. In the buildings in this study, 42% of measurements during 9:00 – 17:00 on weekdays were less than 40% RH and 7% exceeded 60% RH. Indoor RH levels tended to be lower in less tropical regions, in winter months, when outdoor RH or temperature was low, and late in the workday. Furthermore, we also found statistically significant evidence that higher indoor RH levels across the range of 14%–70% RH were associated with lower odds of reporting dryness or irritation of the throat and skin among females and unusual fatigue among males in models adjusted for indoor temperature, country, and day of year.

Practical Implications—We found that it was common for RH to be low in the buildings in this study and that low RH levels were associated with increased reports of symptoms among males and females. Our results suggest that correctly implemented interventions to increase humidity to the acceptable range of moderate RH in office buildings may be useful, particularly during winter, in less tropical climates, and late in the workday, to alleviate occupant symptoms.

Keywords

relative humidity; dry air; symptoms; gender; office buildings; indoor environmental quality

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1. Introduction

Office buildings can impact the health and well-being of office workers, particularly because of the substantial amount of time these workers spend in their workplaces. Humidity is one indoor parameter that can influence multiple aspects of office workers' health and comfort, with implications for their productivity.

One way humidity may impact health is by influencing the spread of viral diseases indoors, as low and high humidity can support viral viability, while low humidity supports viral transmission and weakens humans' immune defenses. Several important viruses, including influenza and SARS-CoV-2, are more viable at very low and very high relative humidity (RH) levels compared with intermediate RH levels.[1–7] Lower RH levels also cause more evaporation of airborne virus-carrying respiratory droplets that have been emitted by an infectious person, and the resulting smaller droplets can remain airborne (i.e., available to be inhaled by and to infect other people) for longer periods of time before settling due to gravity.[3,5] Finally, low RH also impedes mucociliary clearance, an important mechanism for removal of inhaled particles and viruses from the respiratory tract; mucociliary clearance has been found to be faster and thus more effective at intermediate RH levels between 40% and 50% than at levels below 10%.[8,9]

High humidity can promote the presence of indoor contaminants that harm occupant health, while low humidity can increase reported symptoms. For example, high RH levels, typically greater than 60–75% RH, can lead to mold growth,[10,11] which can negatively affect respiratory health by triggering allergic or inflammatory reactions or exacerbating asthma.[11,12] Indoor humidity can also affect emissions of volatile compounds from building materials which may impact occupants' perceptions of indoor air quality.[13,14] On the other hand, several studies report that dry indoor environments can lead to increased reports of dry or irritated eyes, dry skin, and lower and upper respiratory symptoms such as wheeze and sinus congestion.[15–18] To minimize the harmful impacts of viruses, indoor contaminants, and indoor dryness on building occupants, maintaining a moderate indoor RH level between approximately 40% and 60% RH is optimal.

However, there is a general lack of knowledge about how RH levels in real-world workplaces vary over time and geography and how RH might differentially affect the health of different populations. Prior research into the effect of RH on office workers' comfort and health generally compares effects at a few discrete RH values that may not capture the full shape of the relationship between RH and occupant health and may not be generalizable to regions with RH levels that do not match the specific levels under study. Furthermore, this body of prior research does not always distinguish the effect of RH from that of temperature, and it generally has not investigated gender differences in how RH might impact symptoms (even though it has been observed that healthy women report more symptoms than healthy men[19,20]) or considered diverse populations from whom we can generalize to global workers (much of the relevant work has occurred in Nordic countries[15]).

Our goal was to characterize workplace RH levels over one year in 43 office buildings in six countries around the world and to determine how these observed RH levels affected the reported health of 227 male and female office workers. We first evaluated the range of humidity values in these office buildings between 2018 and 2020 to see when and where buildings tended to have intermediate indoor RH values (i.e., 40%–60%) that are protective against respiratory virus transmission and indoor contaminants and that promote human health (e.g., fewer symptoms, better immune defenses against respiratory pathogens). We then identified the building features associated with indoor humidity levels using data from all six countries and evaluated how measured indoor humidity levels from offices in India, the United Kingdom, and the United States were associated with occupant-reported symptoms.

2. Materials & Methods

2.1 Study Design

This analysis used data from the Global CogFx Study, which was a one-year study of office workers in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom (UK), and the United States (USA) between 2018 and 2020. Of the 43 buildings, eight were in China (participated 5/2018 – 8/2019; three in Chengdu, three in Shanghai, and two in Zhuhai), 10 were in India (participated 11/2018 – 11/2019; five in Bengaluru and one each in Chennai, Gurugram, Hyderabad, Mumbai, and Pune), one was in Mexico (participated 3/2019 – 3/2020; in Culiacán), one was in Thailand (participated 2/2019 – 2/2020; in Bangkok), six were in the UK (participated 7/2018 – 7/2019; two in Croydon and one each in Birmingham, Cambridge, London, and Sheffield), and 17 were in the USA (participated 10/2018 – 3/2020; two in Chicago, two in Los Angeles, two in San Francisco, and one each in Boston, Clearwater, Cleveland, Denver, Minneapolis, New York City, Omaha, Overland Park, Phoenix, Seattle, and Washington DC). These buildings were a convenience sample of high quality commercial office spaces. In each office building, a single company participated in study activities. These companies were knowledge work companies with at least 10 employees who worked in the building at least three days a week. In some cases, multiple office locations from a single company participated in the study. In each building, all company employees received an invitation to take the study eligibility survey and between seven and 19 (median 10) office workers per building met the study eligibility criteria (permanent full-time employees who worked at least three days per week in the building who were 18–65 years old, smartphone users, non-smokers, and not colorblind) and subsequently joined the study. The participating office workers hosted environmental sensor packages at or near their desks, answered survey questions in a custom smartphone app, and wore wristband activity trackers for the one-year duration of the study. The study protocol was reviewed and approved by the Institutional Review Board at the Harvard T.H. Chan School of Public Health and individual participants provided informed consent before joining the study.

2.2 Building Assessment

Information about the office buildings in the Global CogFx Study was acquired through an online survey or by email correspondence that was completed by a representative from each participating company. Representatives from all buildings provided information including but not limited to the number of people in the building during operating hours, typical operating hours, building certifications, cleaning practices, and ventilation and filtration practices.

2.3 Indoor Environmental Assessment

In each of the 43 buildings, between one and 30 (median five) environmental sensor packages were deployed at or near participating office workers' workstations. Participating office workers could view real-time data from the sensor installed closest to their workstation in their study smartphone app. Across the 43 participating office buildings, seven different environmental sensor packages were used: the Harvard Healthy Buildings Sensor (a custom sensor package built for the Global CogFx Study at the Harvard T.H. Chan School of Public Health), the Tsinghua IBEM Sensor (a custom sensor package built at Tsinghua University[21]), the Awair Omni (Awair, Inc., San Francisco, USA), the ChemiSense CS-001 Indoor Air Quality Monitor (ChemiSense Inc., Berkeley, USA), the Tongdy MSD-16 Sensor (Tongdy Sensing Technology Corporation, Beijing, China), the Obotrons Indoor Air Quality Monitor (Obotrons Corporation Limited, Bangkok, Thailand), and the Yanzi Comfort (Yanzi Networks AB, Kista, Sweden). These environmental sensor packages all measured air temperature, RH, and carbon dioxide (CO_2) concentration, and all sensor packages besides the Yanzi Comfort (which was used in just one building) measured particulate matter with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$), at approximately one- to ten-minute intervals. Their reported temperature measurement accuracies ranged from ±0.2 C to ±1 C and resolutions ranged from 0.001 C to 0.1 C. Their reported RH measurement accuracies ranged from ±2% RH to ±5% RH and resolutions ranged from 0.01% RH to 1% RH, so it was expected that any inaccuracies would not meaningfully influence the results of our analyses. Raw RH measurements less than 2% RH and greater than 98% RH (approximately 2% of the raw RH measurements) were removed from the dataset before analysis to eliminate extreme measurements outside the recommended operational ranges of some of the sensors. The concentration decay test method[22] was applied to measured CO_2 concentrations from weekdays between 14:00 and 19:00 local time to estimate representative building air exchange rates (AERs) during operating hours for each quarter of the year (December – February, March – May, June – August, and September – November). For full details, see Section 2.4 of Jones et al. 2021.[23]

2.4 Outdoor Environmental Data

Outdoor temperature and RH data for the airport weather station located closest to each of the 43 buildings were obtained from The Weather Company's API Platform (https://weather.com). The distances between participating buildings and the closest airport weather stations ranged from 1.4 kilometers (km) to 49.5 km (median 12.1 km) and the elevation differences between participating buildings and the airport weather stations ranged from 0 meters (m) to 137 m (median 6 m). Outdoor temperature data were used to calculate heating degree days (HDDs) and cooling degree days (CDDs) using a baseline of 65 F (i.e., 18.3 C). For each building, mean daily HDDs and CDDs for each month were calculated by summing the total HDDs or CDDs in the month and then by dividing by the number of days.

2.5 Participant Surveys

At the beginning of study participation, office worker participants downloaded a custom smartphone app through which they were able to answer up to approximately 30 distinct surveys and tests, many of which were repeated multiple times, throughout the study. New surveys and tests were only sent to participants' smartphone apps when participants were at their workplaces, based on geofencing. When participants joined the study, a baseline survey was sent to their smartphone app for them to complete. Information obtained in the baseline survey included age, gender, workstation type, number of other people in their work room, job type, salary range, level of education, other demographic information, and job satisfaction information.

This analysis used data from two different symptom surveys that were both sent to participants' smartphone apps multiple times throughout their year of participation either at pre-scheduled times or when indoor environmental sensor packages measured specific preset threshold values for temperature, RH, or $PM_{2.5}$. These thresholds (described in detail in Appendix A) were designed to ensure that a wide range of environmental conditions would be captured as exposures while participants were responding to the surveys. Each of the two surveys asked participants to select any symptoms they were currently experiencing from a list of symptoms. Survey 1 included the following symptoms: sore or dry throat; dry or itchy skin; dry, itching, or irritated eyes; stuffy or runny nose or sinus congestion; unusual tiredness, fatigue, or drowsiness; difficulty remembering things or concentrating; tension, irritability, or nervousness; and feeling depressed. Survey 2 included the following symptoms: burning or irritated eyes; sore throat; nasal congestion; headaches; migraines; frequent cough; wheezing; multiple colds; shortness of breath; sinus infections; hoarse voice; and sneezing attacks. Participants were able to select one, multiple, or none of the symptoms to indicate their current experience.

2.6 Descriptive Analysis

To evaluate how RH in office buildings varied across the year and across regions and to evaluate whether office buildings typically maintained intermediate RH levels (i.e., 40%–60%), descriptive analyses of indoor RH data were performed. Distribution plots were used to compare hourly device average indoor RH values during the assumed work hours of 9:00 – 17:00 on weekdays across the year in the four study regions: China/Thailand, India, the UK, and Mexico/USA. Data from Thailand and Mexico were grouped regionally with China and the USA, respectively, due to small sample sizes of one building each in Thailand and Mexico.

2.7 Statistical Analysis – Predictors of RH in Buildings

To evaluate the associations between building features and indoor RH, we used a linear additive mixed model.[24] The outcome in the model was building hourly average indoor RH. Covariates in this model included building hourly average indoor temperature, quarterly AER, hourly average outdoor temperature, hourly average outdoor RH, hour of day, region, and building ventilation type. The indoor and outdoor temperature, outdoor RH, hour of day, and quarterly AERs were mean-centered prior to modeling. The model also included a spline for day of year with two degrees of freedom (chosen after reviewing the shape of a penalized regression spline) and a building-specific random intercept. The data used in this model included data from all countries between the assumed work hours of 9:00 and 17:00 on weekdays.

2.8 Statistical Analysis – Associations between RH and Symptoms

We used logistic additive mixed models[24] to evaluate the associations between indoor RH and the odds of experiencing each of seven symptoms. We conducted analyses on the seven symptoms that were reported in at least 10% of completed surveys. The seven symptoms, which were each treated individually as the model outcome, included: dry, itching, burning, or irritated eyes; dry or itchy skin; sore or dry throat; unusual tiredness, fatigue, or drowsiness; headaches or migraines; stuffy or runny nose or nasal or sinus congestion; and difficulty remembering things or concentrating. Each symptom's model only used data from the survey or surveys that listed the symptom.

The main exposure of interest in the models for symptoms, indoor RH, was calculated as the average of RH measurements from the sensor closest to the participant during the hour prior to the time when the participant started the symptom survey. Both linear and spline terms for indoor RH were considered; in the end, a linear term was selected because the relationship between individual symptoms and indoor RH over the range of RH in the dataset appeared to be approximately linear on the logit scale. Other covariates in the model included mean indoor temperature from the sensor closest to the participant during the hour prior to the symptom survey, participant gender (male or female), country, and a spline for day of year with two degrees of freedom (chosen after reviewing the shapes of penalized regression splines). In cases where indoor RH or temperature measurements were not available from the sensor closest to the participant during the hour prior to the symptom survey, indoor RH or temperature was instead quantified by the average of measurements from all other sensors in the building that made measurements during the hour before the participant completed the symptom survey. The models also included an interaction between participant gender and indoor RH to allow the impact of RH on the odds of experiencing a symptom to differ between males and females. Finally, the models included random intercepts for building and for participant. Females were the reference gender in the main models; however, the appropriate terms in model results were summed to also estimate associations between RH and symptom reports among males and the main models were rerun with males as the reference gender to obtain *p*-values for associations between RH and symptom reports among males. Models were also run with an additional covariate representing the number of other people who typically worked in the room where the respondent's workstation was located, but this covariate was not included in final models because its inclusion slightly decreased the models' adjusted R^2 values and model effect estimates were essentially unchanged. Additionally, models were run with a covariate representing indoor CO_2 measurements as a proxy for outdoor air ventilation, but this covariate was not included in final models because it did not explain away or alter the statistically significant associations between RH and symptoms and because indoor CO_2 does not appear to be a confounder of the RH-symptom relationships because indoor RH and indoor CO_2 are not correlated in the study data (Pearson correlation 0.11). Similarly, models were run with RH and temperature calculated as the average of measurements from the sensor closest to the participant between 9:00 local time and the time when the participant started the symptom survey; these representations of RH and temperature were not included in the final models because their substitution for average prior-hour RH and temperature resulted in general in slightly lower adjusted R^2 values while not substantially affecting model effect estimates.

The data used in these models were restricted to data from participants who answered at least one symptom survey during their year of participation and who answered the baseline survey at the start of the study. Further, survey responses were eliminated if there were no temperature or RH measurements made by any sensors in the building during the hour prior to the symptom survey being administered. Finally, only data from India, the UK, and the USA were included in the symptom modeling due to few symptom survey responses from the other three countries. After these restrictions, a total of 1263 responses to both surveys submitted by 227 individual participants were used in the analysis (including 240 surveys submitted by 55 individuals from India, 266 surveys submitted by 40 individuals from the UK, and 757 surveys submitted by 132 individuals from the USA). For Survey 1, Survey 2, and for the combined data from the two surveys, the number of survey respondents per building ranged from one to ten with a median of seven. For Survey 1, the number of responses per person ranged from one to seven with a median of three. For Survey 2, the number of responses per person ranged from one to nine with a median of three. For Survey 1 and Survey 2 combined, the number of responses per person ranged from one to sixteen with a median of six.

All statistical modeling was performed using R version 3.6.2. Statistical significance for model results was evaluated at α=0.05 and suggestive evidence was evaluated at α=0.10.

3. Results

3.1 Building Characteristics

The characteristics of the 43 buildings in this study are presented by region in Table 1. The number of buildings in each region ranged from six buildings in the UK to 18 buildings in Mexico/USA. In all regions, the majority of buildings in the study reported using only mechanical ventilation. Indoor temperatures tended to be lower in Mexico/USA buildings compared to buildings in other regions and indoor RH tended to be lower in buildings in the UK and Mexico/USA compared to China/Thailand and India. UK buildings showed the smallest variation in both indoor temperature and indoor RH.

3.2 Descriptive Analysis of RH across Regions and Across the Year

Low indoor RH measurements during work hours were more common in Mexico/USA and the UK than in China/Thailand and India (Table 2, Figure 1). Hourly device average indoor RH levels across the year were less than 40% RH during 21%, 31%, 45%, and 72% of work hours in China/Thailand, India, Mexico/USA, and UK buildings, respectively. On the other hand, hourly device average indoor RH levels across the year exceeded 60% RH during 25%, 10%, 1%, and 1% of work hours in China/Thailand, India, Mexico/USA, and UK buildings, respectively. This left 54%−59% of indoor hourly device average RH values during work hours between 40% and 60% RH in China/Thailand, India, and Mexico/USA, while only 27% of indoor RH values fell between 40% and 60% RH in the UK.

During the study period, indoor RH during work hours tended to be low (i.e., <40% RH) in each region in the months of December – February (Figure 1). In buildings with all types of ventilation in China/Thailand, Mexico/USA, and the UK, more than half of each region's indoor RH values were outside the range of 40%–60% RH during December – February. Of the four regions, indoor RH was lowest in December-February in the UK, when 94% of measurements were less than 40% RH. On the other hand, indoor RH was most often moderate (i.e., 40%–60% RH) in June – August in all regions (Figure 1). Of the four regions, indoor RH was most consistently between 40% and 60% RH in June – August in India and Mexico/USA, where 84–85% of measurements were between 40% and 60% RH. Cumulative distributions functions separated by daily HDDs and CDDs, rather than by month of year, are presented in Appendix A; these functions support the observations made about Figure 1 and indicate that indoor RH during work hours tended to be lower (i.e., <40% RH) when heating conditions dominated and was most often moderate (i.e., 40%–60% RH) during months when cooling conditions dominated in China/Thailand and India and when neither cooling nor heating conditions dominated in Mexico/USA and the UK.

3.3 Effects of Building on Humidity

The results of the linear additive mixed model analysis (Table 3) also demonstrate that indoor RH varied across the year and by region, after controlling for the other variables in the model, with the spline for day of year and the coefficients for the region variable indicating that the highest indoor RH measurements occurred in the middle of the year and in more tropical regions. Additionally, indoor RH was highest in the morning and tended to decrease throughout the workday. Indoor environmental quality metrics included in the model, temperature and AER, also were associated with indoor RH after controlling for the other variables in the model. As quarterly AER increased, indoor RH increased, possibly due in part to restriction of outdoor air relative to recirculated air by economizers combined with dehumidification by air conditioning during warmer months and reduced RH due to heating in cooler months. As indoor temperature increased, indoor RH decreased, possibly because the vapor pressure of water increases with temperature, so the RH in a parcel of air drops if that parcel of air is heated without the addition or removal of any water. Building ventilation type was not significantly associated with indoor RH after controlling for other variables in the model. Model diagnostics suggested that multicollinearity between outdoor RH and indoor and outdoor temperatures was not present.

3.4 Characteristics of Survey Respondents

Descriptive data about the symptom survey respondents are shown in Table 4. Over half (58–59%) of the survey respondents were from the USA. Respondents were generally well educated, with 44% of respondents reporting holding a doctorate degree while only 5–6% of respondents reported high school or some college as their highest level of education completed. Respondents were split evenly between the two genders. Most respondents worked in open office spaces without partitions and very few (approximately 5%) had private offices.

3.5 Effect of Humidity on Symptoms

The seven symptoms in this analysis can be put into three groups that have previously been used by other researchers[25–27]: dry or itchy skin; mucous membrane symptoms (dry, itching, burning, or irritated eyes; sore or dry throat; and stuffy/runny nose or nasal/sinus congestion); and central nervous system (CNS) symptoms (unusual tiredness, fatigue, or drowsiness; headaches or migraines; and difficulty remembering things or concentrating). The number of surveys in which participants reported each symptom are shown in Table 5. Each of the seven symptoms was reported in at least 10% of surveys. The most prevalent of these symptoms, unusual tiredness, fatigue, or drowsiness, was reported in 17% of responses to Survey 1. The least common of these symptoms were sore or dry throat and dry, itching, burning, or irritated eyes, each of which was reported in 10% of responses to Surveys 1 and 2. Female participants reported a larger percentage of each of the seven symptoms than male participants did (Table 5) even though there were approximately equal numbers of male and female respondents to the surveys (Table 4). The largest gender discrepancy occurred for dry, itching, burning, or irritated eyes; for this symptom, 65% of the symptom reports came from females.

Results of the logistic additive mixed models to evaluate associations between indoor RH and individual symptoms, controlling for indoor temperature, gender, country, and day of year, are shown in Table 6. For Surveys 1 and 2, the indoor RH levels experienced by participants in the hour before the survey ranged from 14% to 70% RH (second percentile 19% RH, ninety-eighth percentile 60% RH) and these RH levels were not correlated with corresponding indoor temperature measurements (Pearson correlation 0.09). For both males and females, higher average indoor RH in the hour before the survey was suggestively or significantly associated with lower adjusted odds of reporting dry or itchy skin. A ten percentage point increase in RH across low and intermediate RH values was associated with a 54% reduction (OR 0.46, 95% confidence interval [CI]: 0.29, 0.75, p=0.002) among females and a 42% reduction (OR 0.58, 95% CI: 0.33, 1.02, p=0.06) among males in the adjusted odds of reporting dry or itchy skin. Among females only, higher average indoor RH in the hour before the survey was suggestively or significantly associated with lower adjusted odds of reporting two mucous membrane symptoms. Among females, a ten percentage point increase in RH across low and intermediate RH values was associated with a 26% reduction in the adjusted odds of reporting dry, itching, burning, or irritated eyes (OR 0.74, 95% CI: 0.52, 1.06, p=0.099), and with a 40% reduction in the adjusted odds of reporting a sore or dry throat (OR 0.60, 95% CI: 0.42, 0.86, p=0.005). Among males only, higher average indoor RH in the hour before the survey was significantly associated with lower adjusted odds of reporting one CNS symptom: a ten percentage point increase in RH across low and intermediate RH values was associated with a 42% reduction in the adjusted odds of reporting unusual tiredness, fatigue, or drowsiness (OR 0.58, 95% CI: 0.36, 0.95, p=0.03).

Indoor RH was not associated with the adjusted odds of reporting dry, itching, burning, or irritated eyes among males (p=0.59); sore or dry throat among males (p=0.31); unusual tiredness, fatigue, or drowsiness among females (p=0.70); headaches or migraines among females (p=0.39) or males (p=0.18); stuffy or runny nose or nasal or sinus congestion among females (p=0.25) or males (p=0.89); or difficulty remembering things or concentrating among females (p=0.87) or males (p=0.36). However, the point estimates of the adjusted odds ratios of females and males reporting each of these symptoms as RH increased were all less than one.

The adjusted odds of reporting the three mucous membrane symptoms and dry or itchy skin were lower, though not significantly so, among males than females. Conversely, the adjusted odds of reporting the three CNS symptoms were higher, though not significantly so, among males than females. There were also some noticeable differences between countries, with the adjusted odds of reporting any symptom in India being lower than in the USA (only significantly so for stuffy or runny nose or nasal or sinus congestion).

4. Discussion

The indoor RH levels we observed in office buildings in six countries were often outside of the range of 40%−60% RH where threats of viruses, mold, and dust mites may be minimized[1–7,10,11,28] and where host susceptibility to respiratory viruses is least compromised.[8,9] In the most extreme instances measured in this study, only 6–7% of hourly device average indoor RH values measured during work hours in UK buildings in December – February and September – November were between 40% and 60% RH, while the remaining 93–94% of RH values were lower than 40% RH. Our results suggest that low indoor RH levels are problematic because they are significantly or suggestively associated with increased reports of dry or itchy skin, two mucous membrane symptoms (females only), and a CNS symptom (males only). These symptom-RH relationships were linear across the full range of measured RH values in one year of data from three countries (i.e., 14%–70% RH). Statistically significant or suggestive associations between RH and symptom reports were not observed for one additional mucous membrane symptom among females, for any of the three mucous membrane symptoms among males, for two CNS symptoms among males, and for any of the three CNS symptoms among females. Based on our modeling of RH and symptom data, if the observed statistically significant associations are causal, increasing RH from 31.8% RH (median RH in UK buildings during work hours in December – February) to 40% RH would result in a 47% (95% CI: −64%, −21%) reduction among females in the adjusted odds of reporting dry or itchy skin; a 34% (95% CI: −51%, −12%) reduction among females in the adjusted odds of reporting sore or dry throat; and a 36% (95% CI: −57%, −4%) reduction among males in the adjusted odds of reporting unusual tiredness, fatigue, or drowsiness.

4.1 Comparison with Prior Research on Indoor Environment and Symptoms

Our results are consistent with prior analyses of RH and symptoms and build upon prior work by evaluating RH as a continuous variable rather than only comparing a limited number of RH levels and by accounting for effect modification by gender. One study in a Finnish office building found that a one percentage point increase in indoor RH was associated with significantly reduced odds of skin dryness (OR 0.96, 95% CI: 0.93, 0.99), skin rash (OR 0.94, 95% CI: 0.88, 1.00), and nasal dryness (OR 0.94, 95% CI: 0.91, 0.97) controlling for temperature.[18] Though not significant, an increase in indoor RH was also associated with reduced odds of eye dryness, pharyngeal dryness, nasal congestion, and nasal excretion.[18] Of note, this study did not account for any personal factors in the modeling, and in fact did not report on demographics of the study population. Gender was an important effect modifier in our analysis and it is possible that the odds ratios for additional symptoms in the Finnish study would have been significant among females or males if gender had been considered. In addition, this prior study also used a limited range of temperatures (21.5–23.7 C) and RH values (20.0%–41.2%), so it is possible they failed to see suggestive or significant effects of indoor RH on reports of eye dryness or throat dryness, as we saw among females, due to the small range of exposures studied. Another study in a Japanese office building found that decreasing RH across a larger range of 25%–60% RH was significantly associated with increased eye irritation, sore or irritated throat, and skin dryness (no other symptoms evaluated), though this analysis also did not consider gender or any other personal or building characteristics.[17] Our analysis builds on the Finnish and Japanese office building results, and other prior work, by demonstrating that associations between indoor RH and the odds of office workers reporting some symptoms exist among workers in multiple regions with varied indoor RH levels and that gender also impacts the association between RH and symptom reports. Moreover, our analysis fills a gap demonstrated by the Finnish office building study and called out in a recent review of impacts of low indoor RH levels on human health[15]: most existing studies compare effects of a small number of distinct RH levels or over a small range of RH levels, and the resulting poor resolution between experimental humidity levels makes it difficult to determine what levels of indoor RH are acceptable. Our modeling provides statistically significant or suggestive evidence for linear relationships between indoor RH and the odds of reporting some symptoms across the full range of realistic RH levels in office buildings. As a result, our work indicates that there is no clear threshold for acceptable indoor RH; rather, building managers can expect consistently fewer symptom reports as RH increases across normal levels.

There is also a body of literature linking indoor temperature and symptoms in buildings.[19,29] One large analysis used data from 95 buildings in the USA-based Building Assessment Survey and Evaluation (BASE) Study to explore the relationship between indoor temperature and humidity measured during one workday and symptoms recalled over the past four weeks.[30] This study found that increased mean building temperature (ranging from 21.6 C to 24.8 C) but not humidity ratio (a mass-based measure of absolute humidity calculated from measured RH ranging from 9.4% to 62.4%) was significantly associated with increased odds of reporting cough and dry or irritated eyes after adjusting for season, gender, smoking, asthma diagnosis (for cough), HDDs, and CDDs. At first glance, these findings seem to be in conflict with our finding that RH but not temperature was significantly or suggestively associated with reduced odds of three symptoms among females and two symptoms among males. However, it is possible that the lack of significant association between humidity and symptoms in the BASE analysis was because they did not account for effect modification by gender (simply controlling for gender in the model, as they did, would not suffice to account for effect modification by gender which was observed in our analysis) or by concurrently evaluating the effects of temperature and absolute humidity (rather than RH), which are expected to be collinear because high absolute humidity levels are only achievable at high temperatures.[5]

4.2 RH and Symptoms in Office Workers

Our finding of significant or suggestive evidence of associations between indoor RH and two of three mucous membrane symptoms in females but not in males could be due to females' increased sensitivity to symptoms. At low RH, symptoms may result from mucous membrane drying. Tear film evaporation is faster, blink frequency also may be higher, and transepidermal water loss is enhanced at low RH.[13,15] Symptom reports may also be affected by humidity-dependent emissions of volatile compounds from building materials. Because the drying of the mucous membranes is not expected to differ by gender, it is possible that both genders in our study experienced this physiological drying, but that only females noticed it. This interpretation is supported by prior literature that indicates healthy females tend to report more symptoms than healthy males on a variety of symptom scales and measures.[19,20] In our study, males reported fewer instances of the seven symptoms evaluated (Table 5) and our model results show that males had non-statistically significantly lower odds of reporting four of the seven symptoms compared to females, after adjusting for RH, indoor temperature, country, and day of year. If females' symptom reports represent the unnoticed and unreported experiences of males, as well as their own experiences, then our finding that females report more mucous membrane symptoms as RH decreases suggests that RH has an important impact on all office workers' physiology throughout their workday. If, on the other hand, males actually do not have a physiological mucous membrane response to low RH and correctly do not report increased mucous membrane symptoms as RH decreases, it is still important to consider the impact of low RH environments on comfort and health of female office workers who did report increased mucous membrane symptoms as RH decreased.

4.3 Strengths & Limitations

This work is limited by its reliance on self-report symptom data which may not represent actual physiological changes, and which are susceptible to being over- or under-reported. However, participants did not have any incentive to misrepresent their symptoms, as they were aware that their individual survey answers would not be shared with their employers. Additionally, while participants did not know we would be analyzing the effects of indoor RH on reported symptoms, participants' responses to symptom surveys could have been influenced by knowledge of current indoor environmental sensor measurements which they could access in the study's custom smartphone app. In this case, the observed associations would still represent the estimated effects of indoor RH on reported symptoms, but the expected mechanisms for these effects could be psychological in addition to purely physiological. Importantly, the use of a smartphone app to ask about participants' current symptoms eliminated the issue of recall bias, which may be present in other studies of reported symptoms experienced over some period of time. This work is also limited by its reliance on volunteer knowledge worker participants in a convenience sample of office buildings, which may reduce the ability to generalize our results to the experience of all office workers in all buildings around the world. Finally, although we accounted for building-level correlation with random intercepts and for country or region-level differences with model covariates, the statistical analyses in this work may suffer from residual confounding by climate, geographic, or cultural factors that vary across the different countries in the study. Nonetheless, this study did include data from 43 buildings in six countries and the year-long concurrent measurement of indoor environmental parameters and administration of symptom questionnaires is a significant advance over prior work that relied on symptom recall or that evaluated associations between non-concurrently measured indoor environmental parameters and symptoms. Furthermore, unlike prior work, we were able to consider additional temporal and personal variables in our modelling of the impact of indoor RH on symptoms and, in particular, to account for effect modification by gender.

4.4 Implications for Humidity in Office Buildings

In our data, it was more common for RH to be lower than 40% RH than to be higher than 60% RH (42% vs. 7% of hourly device average values during work hours across all regions). Indoor dryness generally occurred during winter months and when heating conditions dominated, possibly because heating outdoor air for ventilation without any humidification reduces its RH. During December – February, 35%–94% of indoor RH values in each region were less than 40% RH. Even in June – August, 5%–36% of indoor RH values in each region were less than 40% RH.

While RH was most often too low in our buildings, prior work suggests that elevated RH levels >60% RH can be problematic in buildings. Viability of some enveloped viruses, including SARS-CoV-2,[6] may increase in aerosols and droplets if RH increases above 75–85%[3] and problems like mold and dust mites are more common when indoor RH exceeds 60–75% and 50%, respectively.[10,11,28] The American Society of Heating, Refrigerating and Air-Conditioning Engineers recommends that indoor humidity in occupied spaces be controlled to ensure a dew point of 15 C or lower[31]; at the median temperature during work hours in USA buildings in our study (23.3 C), this recommendation corresponds to a maximum RH of 59%.

Our results suggest that humidity control should be explicitly considered, in addition to consideration of ventilation and temperature targets, when buildings retrofit their ventilation systems and when new buildings are constructed. Where outdoor air is often too humid, dedicated outdoor air systems can provide efficient dehumidification by decoupling humidity control from temperature control.[32] Where outdoor air is often too dry, variable air volume units with adiabatic humidification of outdoor air can provide efficient humidification of incoming outdoor air.[33] When adding humidification to a building, it is important to understand and protect against potential risks of humidification including several severe respiratory diseases. Installing vapor barriers and insulating cold indoor surfaces when adding humidification can help protect against mold. Energy recovery devices, like enthalpy wheels, can also be useful for humidity control in buildings.

5. Conclusions

Our analysis demonstrates that measured RH in the 43 buildings in the Global CogFx Study was often outside the optimal 40%–60% RH zone where risks of viral transmission, dust mites, and mold are expected to be diminished and where human defenses against respiratory pathogens are expected to be unaffected. Some of the variables we found to be linked to low indoor RH include: located in northern latitudes, during winter, at the end of the workday, and when outdoor RH or temperature was low. Although our analysis did not show statistically significant or suggestive evidence for associations between RH and reports of four symptoms among females and five symptoms among males, our analysis also demonstrates that low indoor RH may result in more dry or itchy skin among male and female office workers, more mucous membrane symptoms (dry, itching, burning, or irritated eyes and sore or dry throat) among female office workers, and more unusual tiredness, fatigue, or drowsiness among male office workers. These suggestive or statistically significant associations with RH were observed after controlling for relevant office characteristics including indoor temperature. It is possible, though unlikely given the study design, that participants' access to real-time RH or other environmental data in the study smartphone app could have influenced their symptom reports. The RH-symptom relationships in this study were observed to be linear across the range of RH measurements collected over one year in three countries and, across the low to moderate observed RH values, there did not appear to be a threshold RH above or below which the RH-symptom relationships plateaued. When implemented correctly and carefully, humidification, ideally by a system that has separate humidity and temperature control, to maintain indoor RH between 40% and 60% may be considered as a way to reduce occupant symptoms and promote occupant comfort and health.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data Availability Statement:

The data presented in this manuscript have not been made publicly available due to data confidentiality restrictions.

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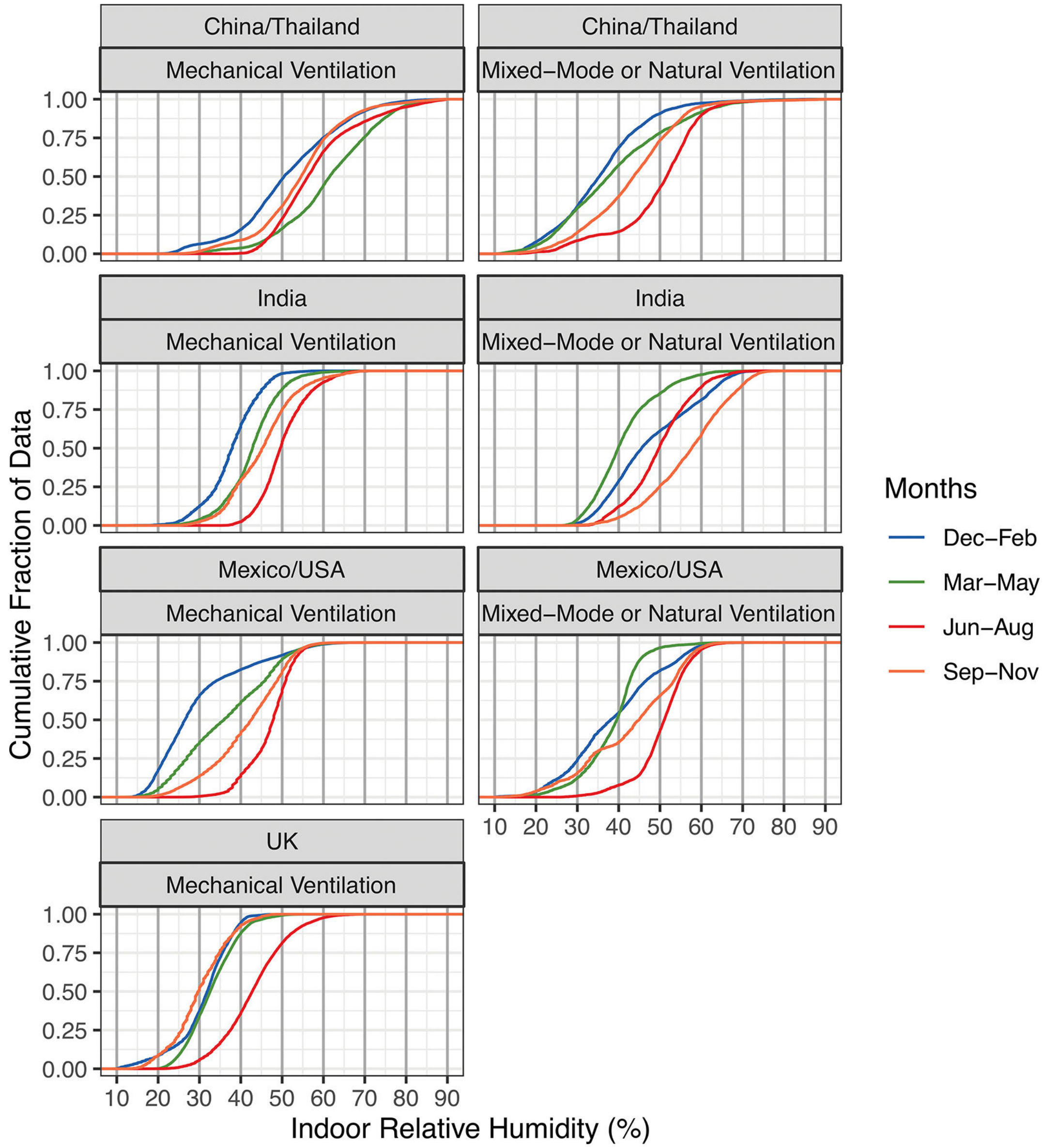

Figure 1:

Cumulative distribution functions of hourly device average indoor RH measurements on weekdays between 9:00 and 17:00 by ventilation type, month of year, and region in the buildings in the Global CogFx Study.

Table 1:

Characteristics of buildings in the Global CogFx Study, by region.

	China/Thailand (n = 9) Median [Range] or n (%)	India (n = 10) Median [Range] or n (%)	UK (n = 6) Median [Range] or n (%)	Mexico/USA (n = 18) Median [Range] or n (%)
Ventilation Type				
Natural	0 (0%)	1 (10%)	0 (0%)	0 (0%)
Mixed-mode	3 (33%)	3 (30%)	0 (0%)	3 (17%)
Mechanical	6 (67%)	6 (60%)	6 (100%)	15 (83%)
Green Building Certification				
No	1 (11%)	7 (70%)	2 (33%)	6 (33%)
Yes	8 (89%)	3 (30%)	4 (67%)	12 (67%)
Healthy Building Certification				
No	8 (89%)	10 (100%)	6 (100%)	9 (50%)
Yes	1 (11%)	0 (0%)	0 (0%)	9 (50%)
Quarterly AER ($hour^{-1}$) †	1.15 [0.21, 2.34]	0.43 [0.15, 1.03]	0.52 [0.38, 1.29]	0.46 [0.19, 3.45]
Indoor temperature (C) during work hours ‡	25.7 [24.3, 27.7]	26.1 [24.8, 26.9]	25.3 [25.1, 25.7]	23.8 [22.0, 25.2]
Indoor RH (%) during work hours ‡	50.3 [40.2, 62.7]	44.5 [36.0, 51.8]	35.5 [31.3, 36.3]	37.4 [27.3, 54.7]
Outdoor temperature (C) during work hours ‡	20.7 [17.6, 30.4]	27.5 [24.7, 31.2]	15.3 [14.0, 17.2]	12.4 [5.3, 22.2]
Outdoor RH (%) during work hours ‡	71.8 [65.6, 80.9]	51.1 [45.8, 64.9]	66.7 [58.7, 70.3]	75.2 [46.4, 82.6]

†Displayed statistics for quarterly AER are the medians and ranges of average building AER across all three-month quarters for all buildings in each region.

‡Displayed statistics for continuous temperature and RH variables are the medians and ranges of building means calculated between 9:00 and 17:00 on weekdays for each building in each region.

AER: air exchange rate

RH: relative humidity

Table 2:

Summary statistics for hourly device average indoor RH measurements on weekdays between 9:00 and 17:00 by ventilation type, month, and region.

			Indoor RH (%)					
Region	**Month**	**Ventilation Type**	**Minimum**	**25th %ile**	**Median**	**Mean**	**75th %ile**	**Maximum**
China/Thailand	Dec-Feb	*All*	*3.9*	*35.8*	*45.4*	*45.9*	*55.5*	*97.9*
		Mechanical	18.5	43.5	50.5	51.5	60.0	94.0
		Mixed-Mode or Natural	3.9	28.4	35.4	36.0	42.1	97.9
	Mar-May	*All*	*2.0*	*38.5*	*54.1*	*51.8*	*64.7*	*98.0*
		Mechanical	26.5	54.4	61.6	61.7	70.0	98.0
		Mixed-Mode or Natural	2.0	28.1	37.4	39.1	48.4	97.9
	Jun-Aug	*All*	*11.7*	*49.0*	*54.7*	*56.2*	*61.0*	*98.0*
		Mechanical	27.3	50.8	56.6	59.2	64.2	98.0
		Mixed-Mode or Natural	11.7	45.7	51.8	50.8	56.6	98.0
	Sep-Nov	*All*	*5.8*	*43.6*	*51.5*	*50.9*	*58.1*	*97.6*
		Mechanical	22.9	48.2	54.6	54.6	60.5	97.6
		Mixed-Mode or Natural	5.8	35.5	43.8	43.6	50.9	97.6
India	Dec-Feb	*All*	*12.0*	*36.2*	*41.2*	*43.3*	*48.4*	*75.3*
		Mechanical	12.0	34.0	38.0	37.7	42.0	59.8
		Mixed-Mode or Natural	24.8	39.1	45.5	47.8	56.8	75.3
	Mar-May	*All*	*18.5*	*37.1*	*41.8*	*42.0*	*46.3*	*75.0*
		Mechanical	18.5	38.7	42.8	42.7	46.7	75.0
		Mixed-Mode or Natural	25.5	35.6	39.9	41.1	45.1	72.6
	Jun-Aug	*All*	*28.7*	*45.7*	*49.7*	*50.1*	*54.3*	*98.0*
		Mechanical	35.4	46.3	49.6	50.3	53.9	98.0
		Mixed-Mode or Natural	28.7	44.7	49.8	49.9	55.1	73.1
	Sep-Nov	*All*	*24.3*	*44.3*	*51.4*	*52.1*	*60.4*	*79.5*
		Mechanical	24.3	39.0	45.2	45.2	50.0	69.2
		Mixed-Mode or Natural	28.7	49.9	57.7	56.9	64.2	79.5
Mexico/USA	Dec-Feb	*All*	*3.6*	*22.4*	*28.1*	*31.4*	*38.8*	*72.4*
		Mechanical	11.4	21.6	26.5	29.5	34.0	71.4
		Mixed-Mode or Natural	3.6	30.2	38.0	38.6	46.4	72.4
	Mar-May	*All*	*6.0*	*27.4*	*36.6*	*36.4*	*45.0*	*72.7*
		Mechanical	6.0	27.0	36.0	36.1	45.7	72.7
		Mixed-Mode or Natural	8.0	34.1	39.5	38.3	42.6	68.8
	Jun-Aug	*All*	*23.8*	*44.0*	*48.0*	*47.3*	*51.1*	*76.0*
		Mechanical	23.8	43.5	47.8	47.0	50.8	76.0

Region	Month	Ventilation Type	Indoor RH (%)					
			Minimum	25th %ile	Median	Mean	75th %ile	Maximum
		Mixed-Mode or Natural	26.0	47.3	51.1	50.4	54.6	71.0
	Sep-Nov	*All*	*3.4*	*35.0*	*42.7*	*41.5*	*49.0*	*68.4*
		Mechanical	6.2	35.2	42.5	41.3	48.7	68.4
		Mixed-Mode or Natural	3.4	33.0	44.9	42.8	53.2	67.2
UK	Dec-Feb	*All*/Mechanical	*6.7*	*27.7*	*31.8*	*30.7*	*35.5*	*92.0*
	Mar-May	*All*/Mechanical	*2.0*	*28.5*	*32.6*	*32.9*	*37.1*	*55.7*
	Jun-Aug	*All*/Mechanical	*14.8*	*37.5*	*42.8*	*42.9*	*48.2*	*97.0*
	Sep-Nov	*All*/Mechanical	*12.3*	*25.7*	*29.7*	*30.0*	*34.8*	*48.5*

RH: relative humidity

%ile: percentile

Table 3:

Results from a linear additive mixed model predicting indoor building average hourly RH (%) on weekdays between 9:00 and 17:00, with a spline on day of year and a random intercept for building. Effect estimates are in units of % RH.

	Effect estimate (95% CI)	***p*-value**
Ventilation (reference = Natural or Mixed-Mode)		
Mechanical	1.01 (−2.44, 4.46)	0.57
Region (reference = China/Thailand)		
India	−4.95 (−9.12, −0.78)	0.02
Mexico/USA	−5.81 (−9.55, −2.06)	0.002
UK	−8.84 (−13.75, −3.94)	0.0004
Indoor Temperature (1 C)	−1.11 (−1.15, −1.08)	<0.0001
Quarterly AER (1 $hour^{-1}$)	1.31 (1.21, 1.41)	<0.0001
Outdoor Temperature (1 C)	0.86 (0.85, 0.87)	<0.0001
Outdoor RH (1%)	0.22 (0.22, 0.22)	<0.0001
Hour of Day (1 hour)	−0.20 (−0.22, −0.18)	<0.0001
Adjusted R^2	*0.68*	

AER: air exchange rate

CI: confidence interval

RH: relative humidity

Table 4:

Characteristics of individuals included in this analysis.

	Median [Range] or n (%)		
	Survey 1 Respondents (n = 211)	**Survey 2 Respondents (n = 215)**	**Survey 1 + Survey 2 Respondents (n = 227)**
Gender			
Male	104 (49%)	112 (52%)	116 (51%)
Female	107 (51%)	103 (48%)	111 (49%)
Country			
India	49 (23%)	50 (23%)	55 (24%)
UK	37 (18%)	39 (18%)	40 (18%)
USA	125 (59%)	126 (59%)	132 (58%)
Workstation Type			
Open space without partitions	141 (67%)	142 (66%)	151 (67%)
Open space with partitions	57 (27%)	60 (28%)	63 (28%)
Shared or single-person private office	11 (5.2%)	11 (5.1%)	11 (4.8%)
Other	2 (0.95%)	2 (0.93%)	2 (0.88%)
Highest Level of Education Completed			
Doctorate	93 (44%)	95 (44%)	101 (44%)
Master’s degree	3 (1.4%)	3 (1.4%)	3 (1.3%)
Professional degree	42 (20%)	43 (20%)	45 (20%)
4-year degree	57 (27%)	58 (27%)	61 (27%)
2-year degree	4 (1.9%)	5 (2.3%)	6 (2.6%)
Some college	8 (3.8%)	7 (3.3%)	8 (3.5%)
High school	4 (1.9%)	4 (1.9%)	4 (1.8%)
Age	32 [21 – 61]	32 [21 – 62]	32 [21 – 62]
# people working in room in which respondent’s workstation is located	40 [0 – 265]	40 [0 – 265]	40 [0 – 265]

Table 5:

Numbers and percentages of completed surveys in which each symptom was reported.

Symptom	Survey	Completed Surveys Reporting Symptom: Females	Completed Surveys Reporting Symptom: Males	Completed Surveys Reporting Symptom: Total	Completed Surveys
		n (% of Total Completed Surveys Reporting Symptom)		n (% of Completed Surveys)	n
Central Nervous System Symptoms					
Unusual tiredness, fatigue, or drowsiness	1	51 (53%)	45 (47%)	96 (17%)	577
Headaches or migraines	2	54 (55%)	44 (45%)	98 (14%)	686
Difficulty remembering things or concentrating	1	50 (63%)	29 (37%)	79 (14%)	577
Mucous Membrane Symptoms					
Dry, itching, burning, or irritated eyes	1 & 2	81 (65%)	43 (35%)	124 (10%)	1263
Sore or dry throat	1 & 2	66 (55%)	54 (45%)	120 (10%)	1263
Stuffy/runny nose or nasal/sinus congestion	1 & 2	113 (55%)	94 (45%)	207 (16%)	1263
Dry or itchy skin	1	53 (64%)	30 (36%)	83 (14%)	577

Table 6:

Results from logistic additive mixed models evaluating whether indoor RH was associated with the log-odds of reporting each symptom. In addition to the variables in the table, the models also included a spline for day of year with two degrees of freedom and random intercepts for building and participant. ORs per 1% RH and 1 C.

	Mucous Membrane Symptoms			Central Nervous System Symptoms			
	Dry, itching, burning, or irritated eyes	**Sore or dry throat**	**Stuffy/runny nose or nasal/sinus congestion**	**Unusual tiredness, fatigue, or drowsiness**	**Headaches or migraines**	**Difficulty remembering things or concentrating**	**Dry or itchy skin**
	Surveys 1 & 2	**Surveys 1 & 2**	**Surveys 1 & 2**	**Survey 1**	**Survey 2**	**Survey 1**	**Survey 1**
	OR (95% CI)	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**
RH_{in} (%)	0.97 (0.94, 1.01) *	0.95 (0.92, 0.99) ***	0.98 (0.95, 1.01)	0.99 (0.95, 1.04)	0.98 (0.95, 1.02)	1.00 (0.95, 1.04)	0.93 (0.88, 0.97) ***
$Temp_{in}$ (C)	0.91 (0.78, 1.06)	1.09 (0.95, 1.25)	1.02 (0.90, 1.16)	1.11 (0.93, 1.33)	0.98 (0.84, 1.14)	1.12 (0.92, 1.37)	1.09 (0.89, 1.33)
Gender (Reference = Female)							
Male	0.21 (0.03, 1.39)	0.23 (0.04, 1.30) *	0.42 (0.09, 1.91)	4.82 (0.52, 44.5)	1.05 (0.19, 5.75)	1.17 (0.08, 16.3)	0.23 (0.02, 2.75)
Country (Reference = USA)							
UK	1.46 (0.66, 3.21)	0.83 (0.40, 1.74)	0.56 (0.28, 1.11)	1.47 (0.70, 3.11)	0.87 (0.43, 1.78)	1.83 (0.78, 4.34)	1.28 (0.57, 2.86)
India	0.68 (0.24, 1.94)	0.86 (0.36, 2.03)	0.25 (0.10, 0.59) ***	0.71 (0.25, 1.96)	0.86 (0.37, 2.01)	0.93 (0.30, 2.86)	0.66 (0.20, 2.20)
RH × Gender (Reference = Female)							
RHxMale	1.02 (0.97, 1.07)	1.03 (0.99, 1.08)	1.02 (0.98, 1.06)	0.96 (0.90, 1.01)	0.99 (0.95, 1.03)	0.98 (0.91, 1.04)	1.02 (0.96, 1.09)

* $p<0.10$

** $p<0.05$

*** $p<0.01$

CI: confidence interval

OR: odds ratio

RH_{in}: indoor relative humidity

$Temp_{in}$: indoor temperature