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Health symptoms in relation to temperature, humidity, and self-reported perceptions of climate in New York City residential environments

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Abstract

Background—Little monitoring has been conducted of temperature and humidity inside homes despite the fact that these conditions may be relevant to health outcomes. Previous studies have observed associations between self-reported perceptions of the indoor environment and health. Here, we investigate associations between measured temperature and humidity, perceptions of indoor environmental conditions, and health symptoms in a sample of New York City apartments.

Methods—We measured temperature and humidity in 40 New York City apartments during summer and winter seasons, and collected survey data from the households' residents. Health outcomes of interest were: 1) sleep quality; 2) symptoms of heat illness (summer season); 3) symptoms of respiratory viral infection (winter season). Using mixed-effects logistic regression models, we investigated associations between the perceptions, symptoms, and measured conditions in each season.

Results—Perceptions of indoor temperature were significantly associated with measured temperature in both the summer and the winter, with a stronger association in the summer season. Sleep quality was inversely related to measured and perceived indoor temperature in the summer season only. Heat illness symptoms were associated with perceived, but not measured, temperature in the summer season. We did not find an association between any measured or perceived condition and cases of respiratory infection in the winter season.

Conclusions—Although limited in size, the results of this study reveal that indoor temperature may impact sleep quality, and that thermal perceptions of the indoor environment may indicate vulnerability to heat illness. These are both important avenues for further investigation.

INTRODUCTION

Indoor temperature and humidity are associated with different adverse health outcomes in the summer and winter seasons. Concerns for the indoor wintertime environment include cold temperature and low humidity. Cold indoor temperature has been associated with exacerbations of chronic obstructive pulmonary disorder (COPD) in one field study (Osman

et al. 2008). Low relative and absolute humidity are of concern with regard to respiratory infection, which exhibits a seasonal pattern with a wintertime peak in temperate countries. Influenza causes between thousands and tens of thousands of deaths in the United States each year (Thompson et al. 2003), and may also contribute to the wintertime peak in deaths due to cardiovascular disease (Siriwardena 2012). Low absolute humidity (AH) has been associated with influenza epidemics, with survival and transmission of the influenza virus in laboratory settings, and in the persistence of influenza virus on household surfaces (Levy et al. 2014; Shaman et al. 2010; Shaman and Kohn 2009; te Beest et al. 2013). Dry air may also promote respiratory infection by drying the mucosal lining of the respiratory tract (Reinikainen and Jaakkola 2003).

In the summer, concerns about the indoor environment largely center on overheating. Extreme heat causes more deaths in the United States than any other weather event (NWS Office of Climate, Water, and Weather Services 2012). High humidity can exacerbate the adverse health effects of heat by impeding the body's natural evaporative cooling processes. Postmortem studies of heat wave mortality have demonstrated that the majority of fatal heat exposures occur inside the home (Fouillet et al. 2006; Wheeler et al. 2013). Morbidity outcomes associated with high heat levels include hospital admissions and emergency medical visits (Hess et al. 2014); one study that assessed these outcomes in relation to measured indoor conditions found evidence of a potential association between increased respiratory distress emergency medical calls and higher indoor temperature (Uejio et al. 2015).

Given the relative shortage of studies that have been able to measure actual indoor temperature and humidity and to associate these conditions with specific health outcomes, it could be extremely advantageous to develop a perception-based approach for evaluating the indoor environment. Perceptions are easy to gather by various survey methods, are non-intrusive, and may, in fact, provide a richer representation of the actual indoor environment than a stationary monitor can provide, as perceptions may take into account factors such as air movement and gradients within and between rooms (Anderson et al. 2013; Ormandy and Ezratty 2012). Validation of such an approach, however, would necessitate corroboration of self-reported perceptions with the aspects of the indoor environment that present risk to human health. To our knowledge only a limited number of studies have investigated these questions. For example, a study in the Netherlands found that high indoor heat exposure was associated with self-perceived health in the elderly (van Loenhout et al. 2016), a Leipzig-based study related subjectively perceived heat stress to indoor temperature (Franck et al. 2013), and a study in Spain found an association between perceptions of indoor air quality and thermal comfort with the presence of fungal growth in the home (Orosa and Oliveira 2012). Only a few field studies have actively monitored temperature and humidity conditions in U.S. residential environments in relation to health outcomes, largely due to the cost and labor-intensiveness of gathering these data (Arena et al. 2010; Nguyen et al. 2013; Quinn et al. 2014; Tamerius et al. 2013; White-Newsome et al. 2012). Concerns about potential health-relevant conditions inside homes, however, have led some researchers to suggest that self-reported perceptions of the indoor environment may be a cost-effective manner of gathering valuable and health-relevant data in population studies. Several large studies have employed this method, for example the WHO Large Analysis and Review of European

housing and health status (LARES) project, for which data were collected in 3373 dwellings across 8 European cities (Ormandy and Ezratty 2012), and a smaller, earlier European study (Bonney et al. 2003). The LARES study found associations between self-reported poor thermal comfort in the home and reports of asthma, allergies, hypertension, and self-reported poor health overall.

Here, we report findings from a study of perceptions of indoor temperature and humidity during the summer and winter seasons from 40 households in New York City (NYC). We relate these perceptions to actual measured conditions in the apartments, to sleep quality, and to reports of heat- and humidity- related symptoms. Although the generalizability of these findings is limited due to the relatively small sample size and incomplete survey reporting, this analysis raises a number of questions to consider in future research.

METHODS

Recruitment and ethical approval

We recruited participants into the study via email and personal outreach using a convenience approach. Recruitment was conducted jointly with Columbia's NIEHS Center for Environmental Health in Northern Manhattan and by WeACT for Environmental Justice, an environmental justice organization located in the Harlem neighborhood of New York. Participants were recruited over a two-year period from 2013–2015, at the start of each of two defined seasons each year. The “winter” season roughly corresponded to November through March, while the “summer” season covered May through September. Any household in the NYC boroughs of Manhattan, Brooklyn, and the Bronx was eligible to participate if the primary household contact was over 18 years of age and had an active email account, and the family did not plan to be away from their NYC residence for more than three weeks during the season.

Households could participate in more than one season if they continued to meet inclusion criteria. No monetary or other incentives were provided to participants for their involvement in the study, and all study participants provided informed consent prior to enrollment. The study protocols and procedures were approved by the Institutional Review Board of Columbia University's Medical Center.

Indoor temperature and humidity measurements

Maxim Integrated DS1923 Hygrochron iButton sensors were installed in the homes to record indoor temperature and relative humidity (RH). These loggers record temperature within the range of -10°C – 65°C , with an accuracy of $\pm 0.5^{\circ}\text{C}$, and RH measurements within the range 0–100%, with an accuracy of 0.6%. Two to four iButtons were installed in each participant's home, depending on the size of the residence. At a minimum, one sensor was installed in the home's main living room and another in the bedroom of the household contact individual. The sensors were installed on walls or furniture at a height of approximately 1.5m, away from windows and heating devices and out of direct sunlight. The sensors were programmed to log measurements every hour, and remained in the residences for approximately 5–6 months, at which time they were removed and the data downloaded.

A new set of sensors was installed at this time if the household continued to participate in the study for a subsequent season.

Outdoor temperature and humidity measurements

NYC's Central Park station was the closest National Oceanic and Atmospheric Association (NOAA) weather station to the homes in this study and is the source of hourly outdoor temperature and dew point temperature readings.

Baseline health and housing information

A survey was conducted at study enrollment to collect data on baseline household variables, including: number and ages of household members, respiratory or cardiovascular diagnoses in the household, number of rooms, bedrooms, and windows in the residence, floor level of residence, type of heating and air conditioning system, use of humidifiers, and building size and age.

Perception and symptom assessment

Online surveys were sent to study participants approximately every three weeks over each season of monitoring. The complete list of questions for each season can be found in the Supplemental Material.

Temperature and humidity perceptions were assessed on 5-point scales from "very cold/very dry" through "neutral" to "very hot/very humid." Temperature and humidity comfort were also assessed on 5-point scales, from "much too cold/much too dry" through "comfortable" to "much too hot/much too humid."

Sleep Quality was assessed for the previous night and the previous three weeks. The options for sleep quality were on a three-point scale: "better than usual," "same as usual", and "more disrupted than usual."

For the summer season we aimed to capture symptoms related to heat-related illness. Much remains unknown about symptom profiles that accurately predict the onset of heat stroke, a very serious health condition that can quickly deteriorate and lead to death (Bouchama and Knochel 2002). For our recurrent surveys, we used a symptom profile that was developed by the NYC Department of Health and Mental Hygiene using data from syndromic surveillance of Emergency Medical Services (EMS) calls and Emergency Department visits related to heat illness. While originally designed to monitor communicable diseases (Heffernan et al. 2004), the syndromic surveillance system has since been expanded to cover non-infectious syndromes, including those related to heat and cold (NYC DOHMH, personal communication). The symptoms pertinent to heat syndromes include one symptom profile associated with "serious heat illness" (including, e.g.: hot, dry skin OR cold, clammy skin; confusion, hallucinations, or disorientation) and another profile of symptoms identified as "heat illness warning signs" (e.g. heavy sweating; muscle cramps; and feeling weak) (NYCEM 2016).

In the winter season, we were interested in symptoms associated with respiratory infections. The symptom questions were drawn from the Common Cold Questionnaire (CCQ) (Murphy

et al. 2013; Powell et al. 2008), which focuses on nine symptoms within four categories (Table 1). “Probable” and “possible” cases of viral infection were defined from these symptom reports per Powell et al. (2008).

Data analysis

Prior studies of the association of temperature and humidity with perceptions and health outcomes have frequently used relative humidity (RH) as the humidity indicator (Davis et al. 2016). This measure of humidity varies as a function of temperature and exhibits strong diurnal and seasonal patterns that largely reflect trends in temperature rather than changes in the moisture content of air. This dependency potentially confounds studies of perceptions of temperature and humidity as separate entities. Further, although RH may be relevant to some health outcomes, measures that quantify the actual moisture content of the air (e.g. specific humidity, absolute humidity, vapor pressure) are more pertinent to other health-relevant outcomes such as viral survival and transmission (Shaman and Kohn 2009). In this analysis, we report humidity levels using vapor pressure (VP), a measure of the partial pressure exerted by water vapor in air. VP was calculated from the recorded indoor temperature and RH using the Clausius-Clapeyron equation (Wallace and Hobbs 2006):

$$e_s(T) = 6.11 \times \exp \left\{ 5.42 \times 10^3 \times \left(\frac{1}{273} - \frac{1}{T} \right) \right\}; \quad [1]$$

where $e_s(T)$ is the saturation vapor pressure of water at temperature T in degrees Kelvin. Vapor pressure is then calculated as follows:

$$VP = e_s(T) \times \frac{RH}{100\%} \quad [2]$$

To align our perception data with measured indoor conditions, perceptions reported for “today” were analyzed with mean measured conditions from the previous 24 hours, and perceptions for “the past three weeks” were analyzed in reference to mean measured conditions across the three weeks preceding each survey response. We analyzed these associations using both bivariate (e.g. perceived temperature predicted by measured temperature) and multivariable (e.g. perceived temperature predicted by measured temperature and measured humidity) models.

The outcome variables in our analyses were self-reported perceptions of indoor conditions, self-reported sleep quality, and reports of symptoms experienced in the household, drawn from the online surveys each season. These outcomes were ordinal and binary in nature, and were analyzed in mixed-effects cumulative or binomial logistic regression models with a random intercept for each household to account for the correlation of effects within households (Christensen 2015). In these models, the exponentiated coefficient for our predictor of interest represents the odds ratio (OR) of the association between the predictor(s) and the outcome.

Our binary outcomes included heat illness during the summer season and viral infections during the winter season (i.e. a survey containing a positive vs. negative report of a case of heat illness or viral infection in the household over the survey period). For these models, the OR is the increase or decrease in odds of the outcome associated with a one-unit increase in the predictor variable.

For our analyses of temperature and humidity perceptions as outcomes, which were rated on a 5-point ordinal scale, the OR represents the odds of a perception being rated “higher” rather than “lower” on the ordinal scale, again associated with a one-unit increase in the predictor variable.

Sleep quality was rated on a three-point ordinal scale where the middle value was that sleep was the “same as usual”. As we were interested in deviations from the normal quality of sleep, we subsetting those surveys whose respondents noted that sleep had been either “better” or “worse” than usual and used this dichotomized variable as the outcome in mixed-effects binomial logistic regression models as described above.

We additionally investigated the association between the household’s seasonal average temperature and vapor pressure and total cases of heat illness (summer season) and probable viral infections (winter season). As we were investigating relationships with household conditions, we restricted the analysis of heat illness symptoms to those that were reported to occur at home. An assumption was made that within-household transmission and infection would be important to the occurrence of viral infections in the winter season. For this analysis we tallied the total number of probable viral infections reported in the household over the season and used this count variable as the outcome in Poisson regression models, adjusting for household size and for the number of surveys completed by the household. The exponentiated coefficients from these models represent the incidence rate ratio (IRR) of probable cases over the season as predicted by indoor conditions.

RESULTS

Study participants by season

We report here on the results from two summer seasons and one winter season. “Summer 1” refers to May 1-September 30, 2014; while “Summer 2” refers to May 1-September 30, 2015. The Winter season refers to November 1, 2014 - March 31, 2015. A total of 40 unique households participated in the study, with an average participation rate of two seasons per household (range, 1–3 seasons of participation per household). The sample size per season was 21 households in Summer 1, 33 in Winter, and 29 in Summer 2. All of the residences were apartments or condominiums located in multifamily buildings. Table 2 presents a summary of the households in the study, compared to citywide averages. The mean household size was 2.3 individuals (range, 1:5), the median number of rooms (not including bathrooms) per household was 4 (range, 1:9) with 2 bedrooms on average. These values are similar to citywide averages, as were the proportion of owners versus renters and the proportion of households with air conditioning. The median age of household members in the sampled households was younger than the citywide median (28.5 versus 35.7), and a

greater proportion of sampled homes were in large buildings (containing 20+ units) than the citywide average.

Seasonal patterns of Indoor and Outdoor Temperature and Humidity

Figure 1 shows the range and distribution of daily mean indoor and outdoor temperature (a) and vapor pressure (b) over the monitored seasons.

Indoor temperature remains within a relatively constrained range throughout the year, whereas outdoor temperature varies greatly. Indoor VP, on the other hand, varies with outdoor VP, although its range is muted with respect to the outdoor values. On average, indoor VP is slightly higher than outdoor VP during all seasons. Indoor mean temperature is also higher than outdoor mean temperature in all seasons, with the difference most pronounced in the winter season but still discernible in summer. The correlations between outdoor temperature and humidity were 0.44 in the summer and 0.81 in the winter (Spearman's rank correlation coefficients), while the corresponding indoor correlations were 0.53 in the summer season and 0.10 in the winter.

Survey Response rates

Five online surveys were administered in Summer 1, six in Winter, and six in Summer 2. The mean response rate per survey was 74.7%. Some households answered more of the surveys than others (range 20.0%–100%); the mean response rate per household was 74.4%. In all, we collected 221 surveys during the two summer seasons, and 137 during the winter season.

We examined whether the households differed in baseline characteristics by survey response rate, and did not find any statistically significant differences between households who responded to more than 75% of the surveys versus those who responded to fewer (data not shown). The households were also not statistically different for mean measured indoor temperature over the season. During the winter season only, “good” responders lived in households that were significantly more humid on average than the poorer responders: mean indoor VP over the season was 7.2 mb in the “good” responders versus 6.2 mb in the other households (t-test p-value = 0.02). Indoor humidity levels were not different by response rate during the summer seasons.

Perception of the Indoor Environment

The most common response to the questions about temperature in the indoor environment was that it was “Neutral” (not too hot or too cold) in both the summer and winter seasons (Figure 2a and 2c), although more respondents reported that the temperature was “Hot” or “Very Hot” in the summer than in winter, when responses of “Cold” were more common than in summer. Seasonal differences in perceptions were more pronounced for humidity, with more respondents reporting “Dry” or “Very Dry” conditions in the wintertime and “Humid” or “Very Humid” conditions in the summertime (Figure 2b and 2d).

Associations between perceptions and measured conditions

We used ordinal mixed-effects regression models to investigate the association between self-reported perceptions of indoor temperature, humidity, and the comfort level associated with each of these variables with measured indoor conditions. We found that results differed by season.

In bivariate models for the summer season (Table 3a, rows 1 and 2), we found that perceived temperature and humidity were each independently associated with measured temperature and with measured humidity, indicating the presence of possible confounding by temperature on humidity perceptions and vice versa. Using a multivariable model in which both measured temperature and measured VP were included as predictors (Table 3a, row 3), we found that perceived temperature was significantly associated with measured temperature when measured humidity was held constant: the odds of rating perceived temperature in a higher category was 2.8 times higher for each one-degree increase in measured temperature, holding VP constant. Perceived humidity was also significantly associated with measured VP when adjusted for measured temperature: the odds of rating humidity in a higher category was 1.39 times higher for each one-millibar increase in measured VP over the previous 24 hours, controlling for temperature.

In the winter season (Table 3b), we again observed significant associations between perceived temperature and both measured temperature and VP in bivariate models. Perceived humidity was not independently associated with measured temperature in this season. In the multivariable models (Table 3b, row 6), the relationship between perceived and measured temperature was significant but less strong than in the summer: OR of 1.8 for the winter season. The OR for the association between perceived and measured humidity was 1.34 for the winter, controlling for temperature.

Sleep Quality

Self-reported sleep problems (rating last night's sleep as "worse than usual") were positively associated with the prior day's measured temperature in the summer season only (OR of 2.28, Table 4a Model 1). Self-reported sleep problems were also significantly associated with perceived temperature (OR = 3.47, Table 4a Model 3). Sleep problems in the winter were not associated with any of the measured or perceived conditions.

Summertime Heat illness symptoms

Overall, there were 27 reported incidents of heat illness symptoms over the two summers: 10 during Summer 1 and 17 during Summer 2 (Table 5). The majority of these cases occurred at home.

For analytic purposes we combined the heat symptoms (whether associated with serious heat illness or heat illness warning signs) into a single "heat illness" outcome variable and isolated only those incidents reported to occur at home (7 cases during Summer 1 and 10 during Summer 2). In mixed-effects logistic regression models, the odds that heat illness reports were associated with higher indoor measured temperature were positive but not significant (Table 6, Models 1 and 3); on the other hand, reports of heat illness were

significantly associated with higher perceived indoor temperature (Table 6, models 5 and 7). The strongest observed associations were with the perception of temperature comfort, both for the same day and over the last 3 weeks. The odds of reporting a case of heat illness with each category increase in the temperature comfort scale was 7.46 times higher and 5.16 times higher for temperature comfort today and over the past 3 weeks, respectively.

We also tested whether temperature and humidity conditions and perceptions averaged over the summer seasons would predict the incidence of heat illness cases, using Poisson models (Table 7). Again, we found no association with the measured variables. As in the results from the more time-dependent approach presented in Table 6, heat illness cases were most strongly associated with self-reported temperature comfort over the summer (Table 7, Model 4). The incidence rate of reported heat stress was almost eight times higher ($IRR = 7.92$) for a unit increase in the temperature comfort scale.

Wintertime Respiratory Infection Symptoms

Of the 30 households who completed follow-up surveys during the winter season, 21 (70%) reported that a household member exhibited symptoms consistent with a possible or probable viral respiratory infection at least once, and 67 total symptom reports were submitted. 43 (63.6%) of these reports were classified as “probable” viral infection cases according to the Common Cold Questionnaire, while an additional 5 (7.5%) were classified as “possible” viral infection cases by the same criteria.

Drier indoor conditions were not associated with a higher incidence of respiratory infection cases. In this sample there was no association between possible or probable viral infection reports and measured or perceived temperature or humidity (Table 8). We also did not find an association between measured or perceived temperature or humidity levels averaged over the winter season (Table 9), although the sign for both measured and perceived humidity was in the expected direction (negative) in all models.

DISCUSSION

In a sample of 40 New York City households, we found that perceptions of temperature and humidity were significantly associated with their measured indoor conditions in both the summer and the winter seasons, and that the association was strongest for temperature in the summer season. The odds of categorizing perceived temperature as higher was almost 3 times higher per measured degree Celsius increase of temperature in the summer season, and nearly 2 times higher per measured degree Celsius increase of temperature in the winter, controlling for humidity. The relationship between measured and perceived humidity, while significant, was less strong: a one-millibar increase in indoor vapor pressure was associated with approximately 30% increased odds of perceiving the indoor environment as more humid, controlling for temperature. These associations were noted despite the fact that a degree of imprecision was inherent in our analysis due to the assumption that perceptions reported “today” referred to the average temperature and humidity over the last 24 hours, which would not be entirely accurate if the survey were completed in the morning.

While temperature receptors innervate human skin, human skin lacks humidity receptors. This fact may help explain why we are limited in our ability to perceive moisture in the air. Despite this, many studies have noted correlations between perceptions of “dry air” and symptoms such as dry eyes and irritated skin; such symptoms have been particularly investigated in the context of airplane cabins, where the moisture content of air is notably low (Grün et al. 2012; Nagda and Hodgson 2001). The mechanism behind perceptions of humidity may, in fact, rely on a combination of factors, including skin wetness and sensation in the respiratory tract (Toftum and Fanger 1999). Most prior studies of humidity perception have investigated perception of relative, rather than absolute, humidity, which may be confounded by temperature if temperature is not kept constant. Here, focusing on vapor pressure (a measure of absolute humidity), we observe an ability to perceive levels of moisture in the air of the residential environment on an absolute scale; however, in the summer the perception of humidity is confounded by temperature, and vice versa. In the winter this confounding is weaker. This finding corroborates prior research that has determined that perception of humidity affects thermal sensation in warm, but not cooler, environments (Jing et al. 2013). We find that when temperature is held constant, perception of humidity remains significant in both the winter and the summer season. Overall, however, the ability to perceive humidity is not as robust as the ability to perceive temperature.

Our finding that sleep quality was inversely related to measured and perceived temperature only during the summer season is also in agreement with a very limited amount of prior research on this subject. For example, elderly residents of the Netherlands reported an increase in summertime sleep disturbances when indoor temperatures were warmer (van Loenhout et al. 2016), and a study of sleep and skin temperature among elderly individuals in Japan found a correlation between higher bedroom temperature and poor sleep only in the summer (Okamoto-Mizuno and Tsuzuki 2010). While climate is but one of many factors associated with sleep quality (e.g. noise, illness, mosquitoes), and our study was not able to discern the contribution of each of these factors, few studies to date have examined the relationship between sleep and temperature conditions in real-world environments. Given the burgeoning literature on the relationship between sleep and health outcomes, this area is ripe for future study.

We found that symptoms associated with heat illness were associated with perceived, but not with measured, temperature in the home. The association was particularly strong for evaluations of temperature comfort, assessed in terms of the respondent’s own comfort level. There are several potential explanations for this finding: first, the experience of possible heat-related symptoms may have led to differential perceptions of the indoor environment. This possibility has been raised in prior research (Brauer et al. 2008). Alternatively, the association could speak to a relationship between perceived levels of heat and differential *vulnerability* to temperature – understanding that numerous individual characteristics affect vulnerability to heat, among them age, health status, and social isolation (Klinenberg 2002; Madrigano et al. 2015). A given level of indoor heat, then, could reasonably pose a risk to some individuals while remaining safe for others. This potential relationship between vulnerability to heat and perceptions of comfort in the indoor environment certainly deserves further study.

Lastly, we identified 43 “probable” cases of viral infection during the winter monitoring season, but found no significant association between indoor humidity levels and reports of viral infections in the winter season. Measured levels of absolute humidity in the homes were quite low throughout the winter (median vapor pressure value 6.5 mb), which is a level that has been associated with elevated rates of influenza virus survival and transmission in laboratory and modeling studies (Koep et al. 2013; Shaman and Kohn 2009). The fact that there was no association between infections and residential humidity levels may speak to the fact that viral transmission can occur in many other environments besides the home, e.g. schools, transportation, and workplaces – and the humidity of the air in these environments may also be low during the winter season.

This study was subject to several limitations. First among them is that this was a convenience sample and the number of participants was relatively small. The findings of this study therefore may not be generalizable to particular subpopulations for whom the health outcomes of interest might have more severe consequences, for example the elderly, the very young, and the chronically ill. In particular, the ability to thermoregulate is compromised in both the very young and the very old; meanwhile, perceptions of thermal risk may also be different in these groups (Gronlund 2014). We did not have sufficient power to fully adjust for factors such as age and health status in our analyses, and we did not collect information on socio-demographic factors such as race and level of education, which could also be related to health outcomes. This information would be valuable to collect and analyze in future studies.

Our case definitions, being based on self-reported symptoms and not on clinical diagnosis, were another inherent limitation of this work. In particular, the case definitions for heat illness were less well defined than for possible or probable viral infection – a fact that reflects the current lack of understanding of the symptom profiles predicting serious heat-related illness. In this work, we included any report of symptoms in the profiles as a heat illness “case” – further research would be required to refine these symptom profiles to better reflect clinical or preclinical diagnosis. Lastly, we do not know if participants were more likely to respond to surveys if they had noticed symptoms in the household. Data missing at random could have reduced the power and precision of the estimates, while differential missing data (e.g. only responding to surveys when there were symptoms) could have led to overestimations of effect.

CONCLUSIONS

This study of perceptions, measured conditions, and health symptoms in 40 New York City households found that measured and perceived indoor temperature were significantly associated in both the summer and winter season, with the association stronger in the summer. Measured and perceived humidity were also significantly associated in both seasons, although the relationship was less strong than for temperature. In the summer season, measures of absolute humidity affected temperature perception, and measures of temperature affected the perception of humidity. Sleep quality was adversely affected by increased temperature in the summer season only, and symptoms of heat illness were associated with perceived, but not measured, temperature in the home. These results suggest

several avenues for further research, including the impact of temperature on sleep quality and the relationship between perception of the indoor environment and vulnerability to heat illness.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Mean and variability of outdoor and indoor temperature and vapor pressure, monitored seasons.

Figure 2. Density Histograms of reported indoor temperature and humidity perception, summer and winter seasons.

Common Cold Questionnaire [source: (Powell et al. 2008)]

Table 1

General Symptoms:	1. Fevers	None	Mild	Moderate	Severe
	2. Chills	None	Mild	Moderate	Severe
	3. Muscle pains	None	Mild	Moderate	Severe
Nasal Symptoms:	1. Watery eyes	None	Mild	Moderate	Severe
	2. Runny nose	None	Mild	Moderate	Severe
	3. Sneezing	None	Mild	Moderate	Severe
Throat Symptoms:	1. Sore throat	None	Mild	Moderate	Severe
Chest Symptoms:	1. Cough	None	Mild	Moderate	Severe
	2. Chest pain	None	Mild	Moderate	Severe
A 'probable' viral infection is where there are moderate symptoms noted in at least 2 of the above 4 categories or mild symptoms noted in 3 or more categories.					
A 'possible' viral infection is where mild symptoms are noted in one category plus a cough. Scoring: none = 0, mild = 1, moderate = 2, severe = 3. Total score equals the sum of all scores.					

Table 2

Characteristics of 40 households.

Characteristic		Sampled households	All New York City households
		Mean (Range)	Mean
Total Household Members		2.3 (1–5)	2.6 ^a
		Median (Range)	Median
Age of household members (years)		28.5 (2–90)	35.7 ^a
Rooms in home		4 (1–9)	4 ^a
Bedrooms in home		2 (0–4)	2 ^a
Floors in building		10.5 (3–34)	NA
Year of construction		1950 (1870–2012)	1948 ^b
		Count (Percent)	Percent
Rent vs. Own			
	Rent	29 (72%)	68.1% ^a
	Own	11 (28%)	31.9% ^a
Units in building			
	2–4	3 (8%)	23.6% ^a
	10–19	1 (2%)	6.3% ^a
	20–99	19 (48%)	47.1% ^a
	100+	17 (42%)	
Located on top floor of building			
	Yes	4 (10%)	NA
	No	36 (90%)	NA
Has Air Conditioning			
	Yes	37 (92%)	88.7% ^c
	No	3 (8%)	11.3% ^c
Owns humidifier			
	Yes	14 (35%)	NA
	No	26 (65%)	NA
Number of seasons participating			
	1	12 (30%)	
	2	13 (33%)	
	3	15 (38%)	

^aSource: U.S. Census Bureau, 2010–2014 American Community Survey 5-Year Estimates^bSource: U.S. Census Bureau, 2015 American Community Survey 1-Year Estimates^cSource: New York City Housing and Vacancy Survey (HVS), 2014

Table 3

Coefficients [Odds Ratios] from ordinal mixed-effects logistic regression models of self-reported perceptions of indoor temperature and humidity modeled against same-day measured indoor conditions, summer and winter seasons.

a. Summer				
			Perceived Temp	Perceived Humidity
1.	Measured Temp	Temp (°C)	1.01 [2.75] ***	0.43 [1.54] ***
2.	Measured VP	VP (mb)	0.23 [1.26] **	0.33 [1.39] ***
3.	Multivariable	Temp (°C) VP (mb)	1.03 [2.80] *** −0.02 [0.98]	0.23 [1.26] 0.25 [1.29] ***
b. Winter				
			Perceived Temp	Perceived Humidity
4.	Measured Temp	Temp (°C)	0.60 [1.82] ***	0.05 [1.05]
5.	Measured VP	VP (mb)	0.18 [1.2] *	0.29 [1.34] **
6.	Multivariable	Temp (°C) VP (mb)	0.59 [1.80] *** 0.17 [1.18] *	−0.0003 [1.00] 0.29 [1.34] **

*
p-value < 0.05;

**
p-value < 0.01;

p-value < 0.001

Table 4

Coefficients [Odds Ratios] for sleep rated “worse than usual” vs “better than usual” from mixed-effects logistic regression models.

Sleep Problems		
a. Summer		
Indoor Measured	Model 1: Temp (°C)	0.83 [2.28] *
	Model 2: VP (mb)	0.21 [1.23]
Indoor Perceived	Model 3: Temp	1.25 [3.47] *
	Model 4: Humidity	0.006 [1.01]
b. Winter		
Indoor Measured	Model 5: Temp (°C)	−0.02 [0.98]
	Model 6: VP (mb)	−0.12 [0.89]
Indoor Perceived	Model 7: Temp	0.61 [1.83]
	Model 8: Humidity	−0.42 [0.65]

*
p-value < 0.05

Table 5

Self-reported incidents of symptoms relating to Heat Illness.

		Summer 1	Summer 2	Total
Serious Heat Illness:	At Home [†]	2	1	3
	At other location	0	1	1
Heat Illness Warning Signs:	At Home [†]	5	9	14
	At other location	3	6	9
	Total	10	17	27

[†] Only symptoms occurring at home were counted as heat syndrome cases for further analysis.

Table 6

Coefficients [Odds Ratios] of heat illness reports predicted by measured and perceived conditions, derived from mixed-effects logistic models, adjusted for number of household members.

Heat Syndrome Cases			
Indoor Measured: Coefficient [OR]	Today	Model 1: Temp today	0.17 [1.19]
		Model 2: VP today	0.07 [1.08]
	Last three weeks	Model 3: Temp 3 wks	0.24 [1.27]
		Model 4: VP 3 wks	−0.02 [0.98]
Indoor Perceived: Coefficient [OR]	Today	Model 5: Temp today Humidity today	0.88 [2.41] 0.09 [1.09]
		Model 6: Temp comfort today Humidity comfort today	2.01 [7.46] *** −0.57 [0.56]
	Last three weeks	Model 7: Temp 3 weeks Humidity 3 weeks	1.26 [3.53] * 0.60 [1.82]
		Model 8: Temp comfort 3 weeks Humidity comfort 3 weeks	1.64 [5.16] *** −0.34 [0.71]

* p-value < 0.05;

** p-value < 0.01;

*** p-value < 0.001

Table 7

Coefficients and incidence rate ratios [IRR] from Poisson models of heat stress cases in the household predicted by measured mean indoor temperature and VP over the summer season; and by average perceptions over the season. All models adjusted for number of persons in the household and number of surveys answered.

Heat Syndrome Cases	
Seasonal Means	Coefficient [IRR]
Model 1: Mean Temperature (°C)	−0.34 [0.71]
Model 2: Mean Vapor Pressure (mb)	−0.16 [0.85]
Model 3:	
Mean perceived Temperature	1.21 [3.35]
Mean perceived Humidity	−1.28 [0.28] *
Model 4:	
Mean perceived Temperature Comfort	2.07 [7.92] *
Mean perceived Humidity Comfort	−0.44 [0.64]

*
p-value < 0.05

Table 8

Coefficients [Odds Ratios] of probable viral infections predicted by measured and perceived conditions, derived from mixed-effects logistic regression models, adjusted for household size.

Probable Viral Infections			
Indoor Measured: Coefficient [OR]	Today	Model 1: Temp today (°C)	−0.15 [0.86]
		Model 2: VP today (mb)	−0.02 [0.99]
	Last three weeks	Model 3: Temp 3 weeks (°C)	−0.15 [0.86]
		Model 4: VP 3 weeks (mb)	0.11 [1.11]
Indoor Perceived: Coefficient [OR]	Today	Model 5: Temp today	0.52 [1.68]
		Humidity today	−0.49 [0.61]
		Model 6: Temp comfort today	0.70 [2.01]
		Humidity comfort today	−0.75 [0.47]
	Last three weeks	Model 7: Temp 3 weeks	−0.05 [0.95]
		Humidity 3 weeks	−0.15 [0.86]
		Model 8: Temp comfort 3 weeks	−0.31 [0.73]
		Humidity comfort 3 weeks	−0.10 [0.90]

*
p-value < 0.05

Table 9

Coefficients and incidence rate ratios [IRR] from Poisson models of reports of “probable” viral infections predicted by mean indoor temperature, mean indoor vapor pressure, and perceptions. All models are adjusted for number of persons in each household and for number of surveys answered.

Probable Viral Infections	
Seasonal Means	Coefficient [IRR]
Model 1: Mean Temperature (°C)	0.12 [1.13]
Model 2: Mean Vapor Pressure (mb)	−0.07 [0.93]
Model 3:	
Mean perceived Temp	0.59 [1.80]
Mean perceived Humidity	−0.50 [0.61]
Model 4:	
Mean perceived Temperature Comfort	0.66 [1.93]
Mean perceived Humidity Comfort	−0.64 [0.53]

*
p-value < 0.05