UNIVERSITY OF CALIFORNIA

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The relationship between indoor environment, outdoor environment, and behavior on indoor air quality and health

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by

Yvonne Shu Hua Yock

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ABSTRACT OF THE THESIS

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Master of Science in Environment and Sustainability

University of California, Los Angeles, 2021

Professor Magali Delmas, Chair

We should be concerned about the impact of indoor air quality on health because in the United States, people spend most of their time indoors. While earlier studies have characterized the odds of developing illness based on the home environment, they have not investigated the behaviors that can ameliorate the negative effect of indoor, outdoor, and behavioral sources. The purpose of this study was to 1) investigate the contributions of indoor, outdoor, and behavioral sources of pollutants on health symptoms, and 2) to identify the behaviors that can worsen or mitigate the number of health symptoms. Data came from two surveys (n=83,284) and include questions on home conditions, outdoor conditions, occupants' behaviors, and health symptoms. I used negative binomial regression and identified that demographics and outdoor characteristics explain 2% of the variability in health symptoms, and maintenance behaviors explain 8% of the variability in health symptoms. Next, structural equation modeling (SEM) was used to examine the behaviors that can mitigate or worsen the number of health symptoms. The results show that maintenance issue such as mold result in significantly more health symptoms ($\beta = .12$, $p <.001$). and factors such as leaks, and frequent long shower may result in an increase in mold. Leaks may cause water stains ($\beta = .39$, $p <.001$) which could lead to molds ($\beta = .47$, $p <.001$). While frequent long shower can result in an increase in mold ($\beta = .05$, $p <.001$), the use of a bathroom exhaust during shower may help to reduce molds ($\beta = -.04$, $p <.001$). In terms of personal behaviors, the presence of carpet ($\beta = .08$, $p <.001$), and smoking also result in an increase in surface dust ($\beta = .17$`, $p <.001$) but frequent vacuuming could mitigate the impact of surface dust on health symptoms ($\beta = -.12$, $p <.001$). Home occupants who live near environmental hazards are also likely to use air purifier ($\beta = .03$, $p <.001$); however, air purifier is associated with more health symptoms ($\beta = .05$, $p <.001$). Based on the findings, it is recommended that home occupants engage in periodic maintenance to prevent issues such as leaks from escalating to molds, regular vacuuming to reduce the accumulation of surface dust. Regarding air purifier, it could be that participants who experienced more health symptoms were more likely to use an air purifier. However, some air purifiers are sources of ozone, therefore home occupants should err on the side of caution when it comes to air purifier (Britigan et al., 2006; Cestonaro et al., 2017).

The thesis of Yvonne Shu Hua Yock is approved.

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Introduction

Objective and Rationale

In the United States, people spend about 65% of their time indoors at home (Leech et al., 2002). Given that we spend so much time indoors, we should be concerned about indoor air quality because the indoor air quality of the space that we inhabit can have an impact on our health (Bluyssen, 2009). Unhealthy indoor air quality has been linked to health conditions such as allergies, respiratory symptoms, and cancers (Sundell, 2004).

A top-down approach that focuses on governmental regulation is the current way of dealing with indoor air quality issues. Governmental regulation has focused on reducing the presence of pollutants in building materials and the installation of a ventilation system in buildings (D. H. Kang, 2020). There is also discussion about possible regulations that could be introduced to restrict the emissions of pollutants, banning the presence of certain pollutants, and introducing a minimum ventilation rate for indoor buildings (Bluyssen, 2009). Occupants' behaviors and the impact that they can play on indoor air quality are often relegated to the sideline. However, occupant's behavior can mitigate indoor and/or outdoor characteristics, as they can worsen indoor air quality. An example of a behavior that can mitigate indoor air quality is when a home occupant affected by wildfire turns on the air purifier to improve indoor air quality (Allen et al., 2011). Behavior that can worsen indoor air quality is when a home occupant uses a cleaning product that contains chemicals that can react with ozone present in the home to form secondary pollutants (Singer et al., 2006).

These two examples highlight the role that behavior can play in affecting indoor air quality. Therefore, the goal of this study is to understand the behaviors that could mitigate or worsen indoor air quality through its interaction with the indoor and outdoor characteristics of the home environment.

Understanding the home occupant's behavior might be the first step in implementing successful interventions to solve the indoor air quality issue. Implementing an effective intervention entails identifying the sources that result in unhealthy indoor air quality, quantifying the contribution of those sources, and the solutions to mitigate the sources of pollution. Indoor air quality can be affected by indoor sources, outdoor sources, and human behavior (Marć et al., 2018). Indoor sources include building materials and type of ventilation system (Leung, 2015a; Spengler & Chen, 2000), outdoor sources include traffic emission, location near a farm, and/or factory (Leung, 2015a), and human behavior includes cooking, usage of a space heater, smoking, and the burning of a candle and incense can contribute to unhealthy indoor air quality (Institute of Medicine, 2011).

The approaches that various studies have taken to quantify the contribution of indoor sources, outdoor sources, and human behavior include 1) identifying the pollutants present in the home as a result of those sources, and 2) calculating the incidence of health symptoms and issues as a result of exposure to those sources. The studies that examined the pollutants present in the house focused on understanding the influence of outdoor sources on the pollutants (i.e. particulate matter and carbonyls, etc.) that were found indoor (Abt et al., 2000; He, 2004; Lee et al., 2002; Liu et al., 2006; Meng et al., 2005). Those studies also investigated the effect of activities such as cooking and cleaning on particle concentration and mass (Abt et al., 2000; He, 2004). The studies that investigated the second approach examined the probability of developing health issues such as asthma and allergies following exposure to indoor sources such as latex wall paint, outdoor sources such as heavy traffic, or behavior such as vacuuming (Awasthi et al., 2013; Lam et al., 2014; Norbäck et al., 2014; Zheng et al., 2013).

Both approaches provide useful insights into the pollutants and sources that affect indoor air quality and the resulting health outcomes. However, there are shortcomings in both approaches. While it is helpful to know the influence of outdoor sources and behaviors on pollutants that are generated in the home, there could be other unmeasured pollutants that can affect the indoor air quality as well. Similarly, it is useful to know the probability of developing health issues following exposure to various indoor, outdoor, or behavioral characteristics. However, a home occupant can be exposed to a multitude of indoor, outdoor, or behavioral sources on a given day which the current studies did not account for, such as exposure to traffic pollutants, vacuuming of the house, and the age of the home. The result of being exposed to various indoor, outdoor, and behavioral sources could result in home occupants having elevated exposure to pollutants thus worsening their health, or it might result in a reduction in health symptoms if some of the behaviors serve as mitigators. While there have been studies that examined the impact of behaviors such as using a range hood while cooking on the concentration of indoor air pollutants (K. Kang et al., 2019; Singer et al., 2012, 2017), and vacuuming to reduce dust particles (Roberts et al., 1999, 2004; Salares et al., 2009), those studies did not investigate the impact of those behaviors on health.

To better understand, the effect of indoor air quality on health outcomes, it is necessary to examine the effect of exposure to multiple sources of pollutants, i.e. indoor sources, outdoor sources, and behavioral sources. In addition to understanding the effect of exposure to multiple sources of pollutants and their contribution to health outcomes, it is also important to understand the behaviors that can mitigate the health effect of being exposed to pollutants. Therefore, the goal of this study is to understand the contribution of multiple sources of pollutants on health and the type of behaviors that can mitigate the effect that unhealthy indoor air quality has on health.

The first aim will be to understand 1) the effect of exposure to multiple sources of negative indoor characteristics and outdoor characteristics, and 2) how behaviors can interact with those characteristics to ameliorate negative indoor air quality and improve health outcomes.

Specifically, the research questions that this study will address are 1) What are the contributions of indoor sources, outdoor sources, and behavioral sources of pollutants to health symptoms? and 2) What are the behaviors that can moderate the effect of living in a home with a poor indoor condition and negative outdoor environment (living near a highway, factory, etc.)?

Literature review

Indoor sources of unhealthy indoor air quality

The possible causes of hazards of indoor source include the building structure (i.e. crawlspace, basement, garage, cladding), the building mechanical system (i.e. air-conditioning system, heating system, and ventilation system), the furnishings in the home (i.e. paint, furniture, etc.), and human occupants (Office of the Surgeon General (US), 2005). Demographics such as the number of occupants, type of home (i.e. single-family home or apartment) can also present a challenge to indoor air quality. Older homes, apartments, and homes with more occupants reported worse indoor air quality (Langer & Bekö, 2013). Researchers in Sweden found that there was a higher level of volatile organic compounds (VOCs) in older homes, with VOCs origin related to indoor sources (Langer & Bekö, 2013). Older homes are also more susceptible to the penetration of outdoor ultrafine particles (UFPs) because they are generally less air-tight

(Stephens & Siegel, 2012). It might also be hazardous to live in a multifamily home as the total bacteria count in the home increases with the number of occupants (Weschler, 2016). Areas with a greater percentage of low-income, minorities, renter-occupied, and lower education attainment households are also likely to be in proximity to hazardous sites (Boone et al., 2014; Gragg et al., 1996; Rhubart & Galli Robertson, 2020).

Some parts of a building structure, such as a crawlspace, basement, garage, and cladding, might pose a problem for indoor air quality. A crawlspace can be problematic because the surfaces of the crawlspace are conducive to mold growth, especially in the summer (Airaksinen et al., 2004). Radon might also be found in the crawlspace area if the crawlspace sits above the soil. Similarly, homes with a basement might suffer from unhealthy indoor air quality (Keskikuru et al., 2018). The correlation between concentrations of VOCs in the living area and basement was found to be moderate across homes in the U.S. (Dodson et al., 2008). The relationship between the presence of VOCs in the living area and the basement suggests that air quality in the living area may be affected if the basement is used as a chemical storage facility (Dodson et al., 2008; Du et al., 2015). Furthermore, there is evidence of elevated levels of microbial VOCs in the basement of some homes despite no report of mold growth in the living area (Ryan & Beaucham, 2013). An attached garage also presents a problem to indoor air quality because homes with an attached garage can report elevated levels of VOCs in the indoor living area (Batterman et al., 2007; Dodson et al., 2008). The cladding is an aspect of building design that also plays a role in indoor air quality. In general, cladding that is of organic material such as wood is more susceptible to mold, though the extent of its susceptibility depends on the chemical composition and finishing (Viitanen et al., 2010).

Other than building structure, mechanical systems also play a role in indoor air quality (IAQ). The type of heating system that homeowners have can make a difference in indoor air quality. Using a wood stove fireplace for heating can increase the particulate matter (PM_{10}, particles with aerodynamic diameters ≤10 μm) and benzo(a)pyrene (BaP) to levels that are above the safe limit (de Gennaro et al., 2015). While the heating system is not a major contributor to UFPs, it still produces UFPs and some heating systems produce more UFPs than others. Specifically, an electric baseboard heater and a wood-stove heater result in a greater concentration of UFPs than a forced-air natural gas furnace (Weichenthal et al., 2007). While the use of a central heating system can enhance thermal comfort for the occupants, the overall increase in indoor temperature, can result in reduced air exchange rate making the home a conducive environment for the proliferation of dust mite and mold (Hirsch et al., 2000).

Apart from building structures and mechanical systems, home furnishings also contribute to indoor air quality. Homes with carpets are reported to have more dust particles than homes without floor covering, carpeted homes also reported higher rates of dust particles resuspension. The health problems associated with carpeting include respiratory problems and symptoms of sick building syndrome (Becher et al., 2018). Furnishings such as carpet, wood furniture, and wall covering are also sources of VOCs (Bernstein et al., 2008; S.-S. Kim et al., 2008; Rösch et al., 2014). Exposure to VOC is linked to eye, nose, and throat discomfort, coughing, and headache (Bernstein et al., 2008).

Outdoor sources of unhealthy indoor air quality

There are various negative environmental hazards that home occupants can be exposed to depending on the location of their homes. Home occupants who live near a restaurant can be subjected to elevated levels of polycyclic aromatic hydrocarbon (PAH) (Chen et al., 2012). It is also not ideal to live downwind of an airport as the concentration of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), black carbon, and PAH are much higher than in homes that are not downwind of the airport (Hudda et al., 2020). Homes that are near farms might also find chemical components of pesticides in their house dust (Rudel et al., 2003). Tetrachloroethylene (PCE) is a chemical that is emitted from dry cleaners. Homes that are situated close to dry cleaners are at risk of heightened exposure to this compound (McDermott et al., 2005). Living near a highway or major traffic can affect the indoor air quality adversely as well because occupants might be exposed to pollutants such as PM_{10}, $PM_{2.5}$, VOCs, and NO_2 and such exposure can have a debilitating effect on cardiovascular and respiratory health (Brugge et al., 2007; Kuhn et al., 2005). A residence that is close to one or more industrial sites is a concern too as some studies have found an increased cancer risk among those home occupants (Benedetti et al., 2001). Finally, a high-humidity climate can encourage mold growth (Lopez-Arce et al., 2020a) but it can also hinder the resuspension of dust particles (Salimifard et al., 2017).

Behavioral sources of unhealthy indoor air quality

Behaviors that affect indoor air quality differ in their impact depending on whether it is a short-term, daily, or long-term behavior. Activities such as cooking and smoking result in an elevated level of $PM_{2.5}$ (K.-H. Kim et al., 2011; Ni et al., 2020). However, the extent of its effect depends on the frequency of cooking and smoking. For smoking, the cumulative exposure to $PM_{2.5}$ has been linked to an increase in lung damage and insulin resistance (Jiang et al., 2018). Some scented cleaning and grooming products contain VOCs which can have a detrimental effect on health, those VOCs can also react with ozone (O_3) to form secondary pollutants (Clausen et al., 2001; Nazaroff & Weschler, 2004; Singer et al., 2006). Similar to exposure to

$PM_{2.5}$, cumulative exposure to VOCs is also linked to worse health outcomes (Bari et al., 2015; Sexton et al., 2005).

Thus far, I have discussed deleterious behaviors that affect indoor air quality. However, there are behaviors that home occupants can engage in to improve indoor air quality, for instance engaging in periodic maintenance of the house. Maintenance behaviors such as checking for mold, leaks, and dust are crucial to maintaining optimal indoor air quality. There are a few factors that can contribute to mold growth: high humidity, high temperature, ample building moisture, and inadequate ventilation (Lopez-Arce et al., 2020a). Home occupants should inspect their homes for mold if they are susceptible to it because mold exposure can result in respiratory illnesses and allergies (Crook & Burton, 2010). In the same vein, it is important to check for leaks as well because they can result in molds if left unchecked (Institute of Medicine, 2004). House dust can contain a long list of compounds from various indoor and outdoor sources such as tobacco, fragrances, solvents, adhesives, and combustion byproducts. The absorption of house dust occurs through dermal contact and ingestion, with toddlers more at risk for ingestion of house dust (Mercier et al., 2011). Despite the benefits of frequent home maintenance, renters are less likely to engage in maintenance than owners. The difference exists because owners are financially motivated to ensure that their home is in optimal condition and they are more likely to enjoy the fruit of their maintenance since they are less mobile than renters (Dietz & Haurin, 2003).

While it is best to avoid behaviors that harm indoor air quality, there are some behaviors such as cooking that are inevitable. Nevertheless, there are behaviors such as using a range hood while cooking, turning on the bathroom exhaust fan while showering, and using a High-efficiency Particulate Air (HEPA) vacuum cleaner to remove dust particles from the carpet that may prove helpful in mitigating unhealthy indoor air quality. Using a range hood with a high capture efficiency and a strong fan can minimize the number of pollutants that are generated while cooking (Singer et al., 2012). Turning on the bathroom exhaust fan while showering can increase ventilation (Wilson et al., 2020) and that can reduce the incidence of mold (Lopez-Arce et al., 2020b). Vacuuming can cause dust particles to be resuspended and emitted from the vacuum cleaner motor but using a HEPA vacuum cleaner can reduce significantly the percentage of dust particles that are resuspended and emitted (Lioy et al., 1999).

Methods

Instrument

This study investigated the relationship between indoor, outdoor, and behavioral characteristics and used the number of active health symptoms experienced as a dependent variable, which were collected through a secondary data analysis of home occupants. The secondary data were analyzed with a negative binomial regression model because the dependent variable is a count outcome with overdispersion. There were five models in the stepwise negative binomial regression model.

Variables used in this study comes from the administration of two surveys. The first survey was administered by the team at Hayward Score, a California company that has developed a scoring system to evaluate the health impacts of homes among volunteer participants. The volunteer participants survey includes a series of questions on home conditions (i.e. level of maintenance, building structure, building design), outdoor conditions (such as proximity of freeway, industrial site or airport, etc.), behaviors (cooking, smoking, opening windows, vacuuming, removing shoes, etc.) and health symptoms (respiratory such as sinus congestion, physical, such as aching muscles or joints/lower back pain; and cognitive, such as moodiness or agitation, and depression). It includes more than 250 variables on home conditions, outdoor conditions, behaviors, and more than 20 health symptoms. The full list of variables and summary statistics can be found in Appendix A. The second survey was administered to paid participants through the SurveyMonkey platform. One of the drawbacks of the survey with paid participants is that it has fewer variables than the survey with volunteer participants. The variables missing from the paid participants survey include demographics- story, tenure, exterior in the sun, maintenance - count of active leaks, behaviors - chemical storage, scented products, windows are open, frequently take a long shower, shoes are removed, and frequency of vacuuming.

Participants and sampling

Surveys were administered to two groups of U.S. participants. The first survey was administered and collected through a platform developed by the Hayward team to 70,540 U.S. volunteer participants between 2016 and 2020. Volunteer participants in the first survey, were mainly recruited through Google Ads, with the rest recruited through display advertising online, two campaigns on Facebook, and direct traffic from the Hayward score website, blog post, or news articles. Google Ads is an online Search Engine Marketing (SEM) platform where advertisers bid to display brief advertisements, service offerings, product listings, or videos to web users. The main campaigns for the volunteer survey revolved around keywords such as mold, air quality, water issues, breathing, respiratory, asthma, and military. The most successful ad campaigns were those that included the keyword “mold.” All ad campaigns emphasized that the calculation of the score by Hayward Score was free of charge and included questions such as: “Is your home impacting your health?” or “Is your home making you sick?” The advertising efforts started in February 2017 and there were higher rates of response during regular working hours (8:00 am to 5:00 pm), with some fluctuation over the days of the week. With the Google Ads campaigns, the likelihood of participants seeing a Hayward Score ad or sponsored link after they googled keywords that were used in the campaign likelihood depended on Google algorithms. With the display advertising online, the Hayward Score survey ad appeared based on the user's search history or through a retargeting process after the participant has visited the Hayward Score website. However, display advertising was not as effective as Google Ads. Two Facebook campaigns targeted individuals with asthma and members of the military. Lastly, a smaller number of respondents (about 10%) were recruited through the Hayward Score website or links provided in blog posts or news articles.

The second survey was administered and collected through a SurveyMonkey platform to 16,286 paid U.S. participants in 2020. The paid participants received a request to participate in the survey through mobile app push notifications, through their SurveyMonkey Contribute account, or the SurveyMonkey Rewards app.

Preparation of dataset

The volunteer participants and paid participants survey were merged and table 1 presents the demographics characteristics of the merged dataset.

Table 1

Demographic characteristics of participants

	Mean	SD
Type of housing		
Single family, detached	0.65	0.48
Multi-unit low-rise (<3 stories)	0.07	0.26

Multi-unit high-rise (>3stories)	0.08	0.28
Mobile/manufactured home	0.20	0.40
Ownership		
Own	0.60	0.49
Rent	0.39	0.49
Military	0.02	0.12
Number of people in the household	2.81	1.66

The demographic characteristics covered in table 1 include housing type, ownership, and number of people in the household. Majority of the participants (65%) resided in a single-family home. Most of the participants were also homeowners (60%). There were on average 2.81 people in the participants' household. A comparison of the demographic characteristics of volunteer participants and paid participants can be found in Appendix B.

Some of the variables were on a different scale across both the volunteer and paid participants surveys and those variables were recoded so the datasets could be merged. Other variables were recoded for ease of interpretation. Table 2 presents a summary of the variables that were recoded.

Table 2

Recoding of variables for the merging of datasets

Variable	Scale on the volunteer participants survey	Scale on the paid participants survey	How the variable was recoded
Frequency of meal preparation	no cooking at all, cooking limited (9 or fewer times), cooking often (10 or more times)	0 to 4 times, 5 to 10 times, 11 or more	This variable in the paid participants survey was recoded to be on the same

Variable	Scale on the volunteer participants survey	Scale on the paid participants survey	How the variable was recoded
			scale as the volunteer participants survey
Count of leaks	Leak 1- 0 or 1 leak Leak 2 – 0 or 1 leak	0 to 5 leaks	This variable was recoded for both sets of surveys to 0, 1, 2 or more leaks
Apartment	single-family home, mobile home, multi-unit high-rise (> 3 stories), multi-unit high-rise (< 3 stories)	single-family home, mobile home, multi-unit high-rise (> 3 stories), multi-unit high-rise (< 3 stories)	Single-family home and mobile home were recoded to form landed home, and multi-unit high-rise and multi-unit low-rise were recoded to form apartment
Home ownership	renter, owner, military	renter, owner, military	Military was dropped as this made up less than 2% of the sample in both surveys
Frequency of maintenance	expertly/well maintained, somewhat maintained, deferred maintenance		Reverse-coded
Windows are open	windows are shut, rarely/never open, yes-seasonally, yes-year-round		recoded to no, windows are shut, yes- windows are open
uses an unvented range hood while cooking			Reverse-coded
Vacuum frequency			Reverse-coded
Number of pets	Computed by summing up the number of cats, number of dogs, and number of other pets variable. Ranged between 0 to 24 pets.	0 - 7 pets	Recoded to 0 - 6 and more pets

The median income by zip code variable was created by matching participants' zip code to the median income for that zip code. The Median income by zip code was calculated by aggregating income data from the American Community Survey (ACS) (University of Michigan Population Studies Center, 2020).

Some of the variables were created by summating a list of variables. The number of pests variable was computed by summing up the presence of roaches, mice, bat, termite, and ant. The volunteer participants survey includes a question on the presence of mite, but this was not present in the paid participants survey, therefore mite was not included in the number of pests variable. The chemical storage indoor variable was computed by summing up chemical storage cleaning supplies, chemical storage grooming supplies, chemical storage art supplies, and chemical storage gardening supplies in the bedroom, inside the house, and attachment to the house. Finally, the dependent variable, the count of active health symptoms was computed by summing up the count of 23 active health symptoms. A variable indicating whether the observation was from the volunteer participants or the paid participants was also included in the merged dataset.

Negative binomial regression model

A negative binomial regression model was chosen for this analysis because the dependent variable is the count of active health symptoms, which is a count outcome and due to the overdispersion of the outcome variable as evident from the Pearson χ^2 dispersion statistic of 4.89, $p < .001$. Figure 1 illustrates the observed proportion of outcome variables with the Poisson model and the negative binomial model, and the negative binomial model was found to be a better fit.

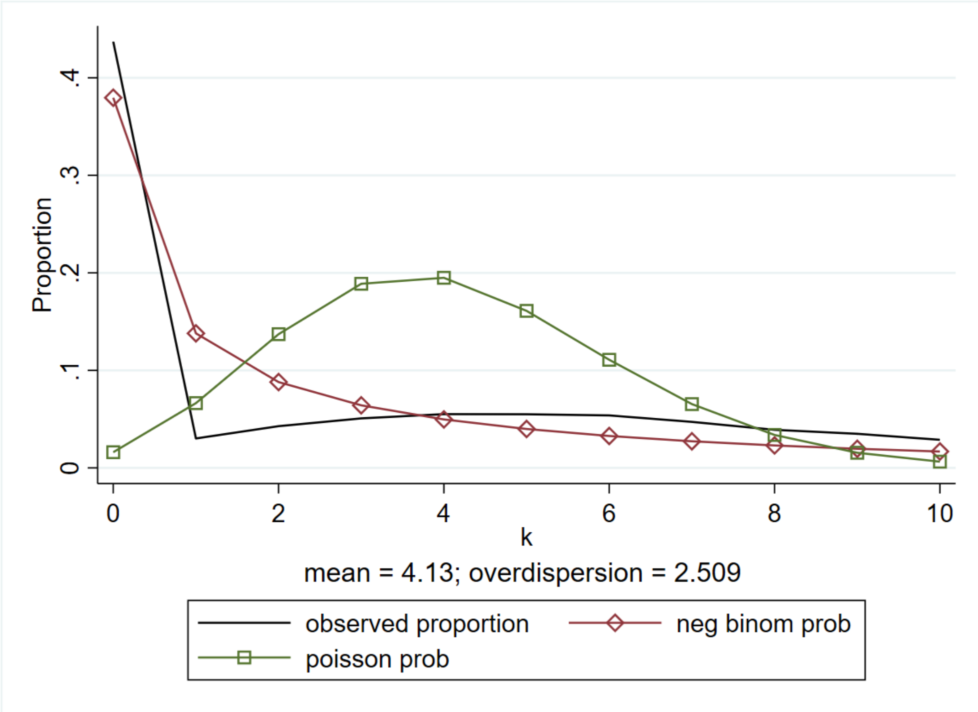

Figure 1. Graph of observed proportion of outcome variable along with the Poisson and negative binomial probability.

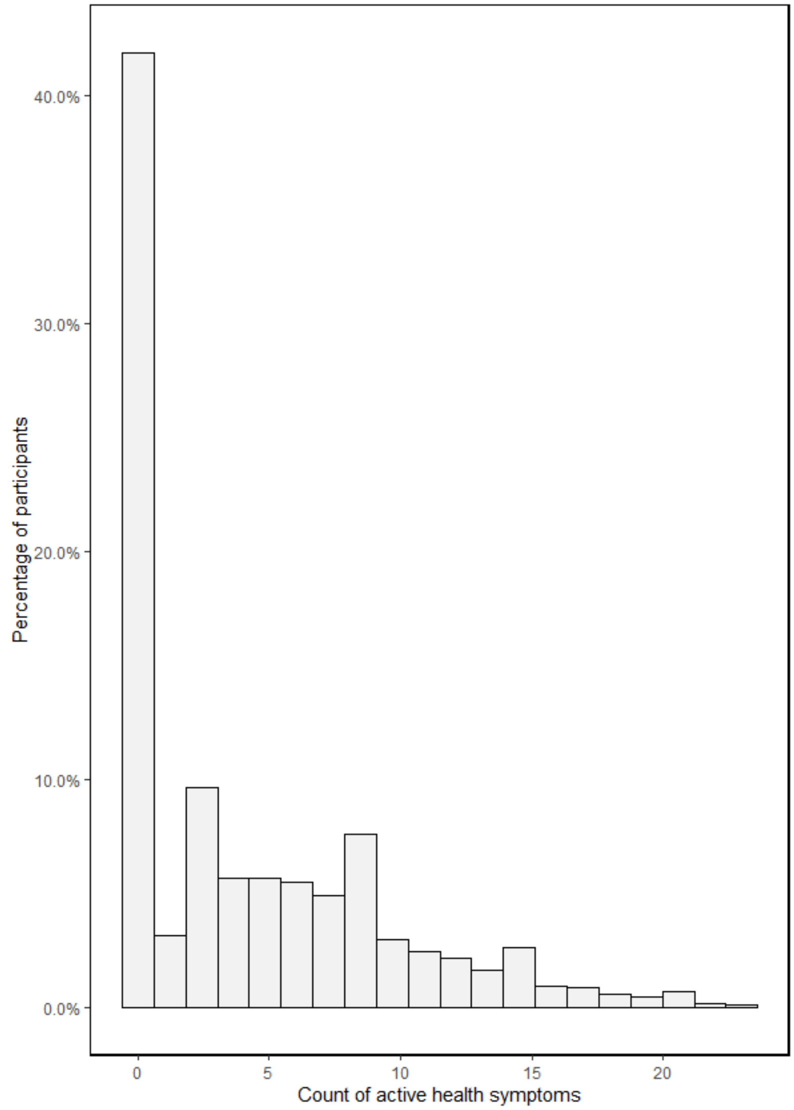

Figure 2. Histogram of the distribution of participants from merged dataset with 0 to 23 active health symptoms (N=77,054)

Figure 2 illustrates the range of active health symptoms (between 0 to 23 health symptoms) experienced by the participants. Close to half of the participants (44%) had zero active health symptoms.

The dependent variable is the count of active health symptoms and the independent variables represent the following categories: 1) demographics characteristics, 2) indoor characteristics, 3) environmental hazards,4) maintenance behaviors, and 5) personal behaviors.

I arrived at the categories for the indoor, outdoor, and behavioral characteristics through discussion with the Hayward team and referring to the literature from the Well Building Standard (International Well Building Institute, 2019) for the categorization of behavioral characteristics and a report from the Surgeon's General workshop (Office of the Surgeon General (US), 2005). The report from the Surgeon's General workshop detailed the building structure and/or building design, the type of ventilation and heating system as key elements of a home indoor characteristics. The Well Building Standard matrix is comprehensive as it covers elements related to air, nourishment, comfort, mind, light, water, and fitness. For this study, my focus will be on the elements related to air quality in the home, such as ventilation effectiveness, microbe and mold control, pest control, and toxic material reduction.

The equation used for the negative binomial regression model is:

log (count of active health symptoms) = b_0 +b_1 demographics+ b_2 indoor characteristics + b_3 outdoor characteristics + b_4 maintenance behaviors + b_5 personal behaviors

There were five models in this negative binomial regression stepwise analysis. Model (1) includes demographic variables such as building type, story of home, and square footage, model (2) features the variables in model 1 and variables related to indoor characteristics such as basement, and heating system, model (3) features the variables in model 1, model 2, and variables related to outdoor characteristics such as the presence of environmental hazards, model (4) features the variables in model 1, model 2, model 3, and variables related to maintenance behaviors such as frequency of maintenance, noticeable odors, and noticeable surface dust, model (5) includes variables in model 1, model 2, model 3, model 4, and variables related to personal behaviors such as frequency of meal preparation and number of pets.

Structural equation model (SEM)

After identifying the outdoor characteristics and the maintenance behaviors that affect health outcomes, structural equation modeling (SEM) was performed to identify the behaviors that mitigate the effects of outdoor characteristics and maintenance behaviors with the merged dataset. The rationale for performing an SEM is to understand what are the behaviors that can mitigate or worsen the impact of the outdoor characteristics and maintenance behaviors that I have identified in the regression model as having a significant effect on health symptoms. Despite its advantage, there are some drawbacks to SEM. Some of the drawbacks include the fact that the chosen SEM model is just one of the many conceivable models which results in a satisfactory fit of the data, the fit of an SEM model is particularly sensitive to the omission of important variables, and multicollinearity among variables, and a good SEM model fit could be due to weak correlations between the observed variables which is not optimal or due to the strong relationship between measurement rigor and estimation rigor which in this case is optimal (Tarka, 2018).

I hypothesized the relationships that 1) mediate count of active leaks and count of active health symptoms 2) mediate frequent long shower and count of active health symptoms 3) mediate presence of carpet in the house and count of active health symptoms 4) environmental hazards and count of active health symptoms in the SEM model.

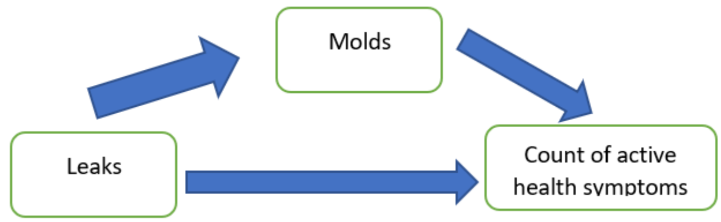

Figure 3. Relationship between leaks and count of active health symptoms

Figure 3 illustrates the hypothesized relationship between leaks and count of active health symptoms. The causal pathway through which molds might act, i.e. mediate the relationship between leaks and count of active health symptoms could be due to leaks resulting in an increase in mold. The increase in mold results in home occupants developing more health symptoms.

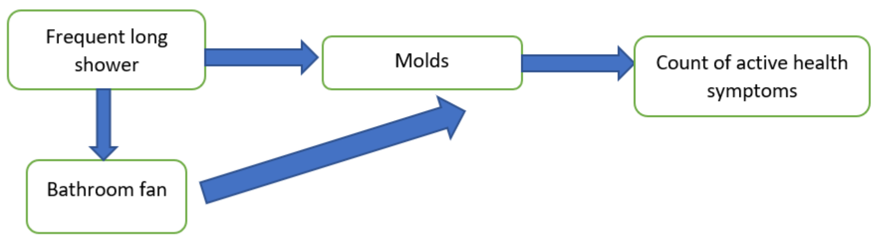

Figure 4. Relationship between frequent long shower and count of active health symptoms

Figure 4 illustrates the hypothesized relationship between frequency of long shower and count of active health symptoms. The causal pathway through which molds might act, i.e. mediate the relationship between long shower and count of active health symptoms could be due to frequent long shower resulting in an increase in mold. I hypothesize that the use of a bathroom fan that exhaust outside can moderate the effect of long shower, thereby diminishing mold growth.

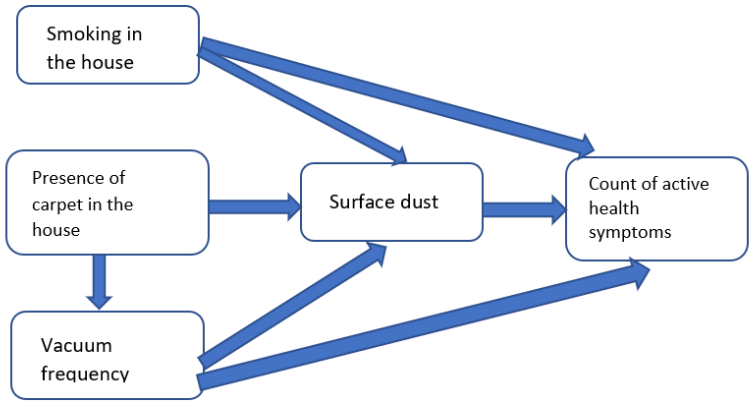

Figure 5. Relationship between presence of carpet and smoking, and count of active health symptoms

Figure 5 illustrates the hypothesized relationship between presence of carpet and smoking, and count of active health symptoms. The causal pathway through which surface dust might act, i.e., mediate the relationship between presence of carpet and smoking in the house and count of active health symptoms could be due to the presence of carpet and smoking resulting in an increase in surface dust. I hypothesize that frequent vacuuming can moderate the effect of surface dust, thereby reducing the number of health symptoms.

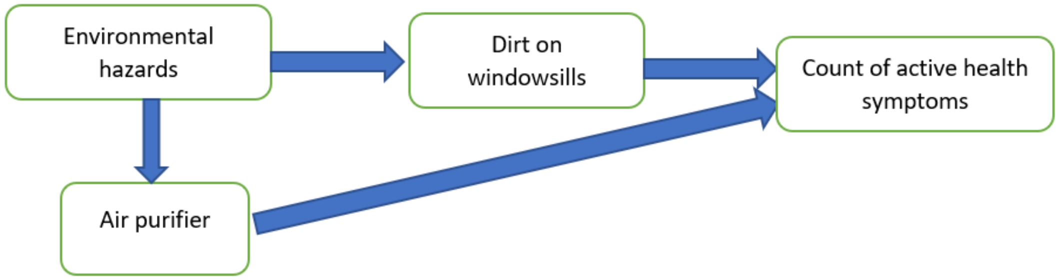

Figure 6. Relationship between environmental hazards and count of active health symptoms

Figure 6 illustrates the hypothesized relationship between environmental hazards and count of active health symptoms. The causal pathway through which dirt on windowsills might act, i.e. mediate the relationship between living close to environmental hazards and count of active health symptoms could be explained by the increase in dirt on windowsills as a result of living close to environmental hazards. I hypothesize that the use of an air purifier can moderate the effect of living close to environmental hazards, thereby reducing the number of health symptoms.

Results

Correlation of variables

Polychoric correlation was performed to obtain the correlation of the study's variable because some of the variables are binary and this technique will yield more reliable estimates for binary estimates as compared to Pearson correlation. Table 3 presents the results from the polychoric correlation. In general, variables describing maintenance behaviors such as mold $r(85986) = .33$, $p < .001$, water stain $r(85996) = .34$, $p < .001$, surface dust $r(85961) = .42$, $p < .001$, odor $r(87164) = .45$, $p < .001$, and leaks $r(64715) = .26$, $p < .001$ have the strongest positive correlation with count of active health symptoms. The greater the incidence of negative maintenance behaviors such as mold, water stain, surface dust, odor, and leaks, the more likely home occupants are to suffer more health symptoms. However, positive maintenance behavior in the form of frequent maintenance results in the likelihood of fewer health symptoms $r(85111) = -.34$, $p < .001$. Other than maintenance behaviors, environmental hazards such as living near industrial area $r(90200) = .19$, $p < .001$ and highway $r(90200) = .14$, $p < .001$, as well as personal behavior such as smoking $r(77241) = .26$, $p < .001$ are positively related to more health symptoms, that is the presence of these factors are likely to result in more health symptoms.

Table 3

Correlation of variables

		1	2	3	4	5	6	7	8	9	10	11	12
1	health symptoms												
2	range of year built	0.07***											
3	sq footage	-0.12***	-0.11***										
4	no. of people household	0.06***	-0.02	0.21***									
5	garage	-0.13***	-0.31***	0.42***	0.06***								
6	basement	-0.05	0.34***	0.34***	0.08***	0.2***							
7	crawlspace	0.06***	0.14***	0.04*	0.02	-0.09***	-0.29***						
8	hazard farm	0.08***	-0.12***	0.13***	0.05	0.09***	0.09***	0.18***					
9	hazard airport	0.11***	-0.02	-0.09***	0.02	-0.08***	-0.1***	-0.02	0.13***				
10	hazard highway	0.14***	0.1***	-0.17***	-0.05***	-0.09***	-0.07***	-0.04	-0.1*	0.24***			
11	hazard industrial	0.19***	0.1***	-0.11***	0.02	-0.11***	0.02	0.05***	0.12***	0.33***	0.23***		
12	hazard coffee	0.05***	0.01	-0.11***	-0.01	-0.08***	-0.06**	-0.07***	-0.04	0.15***	0.2***	0.12***	
13	hazard drycleaner	-0.02*	0.06***	-0.13***	-0.03	-0.1***	-0.06*	-0.17***	-0.22***	0.22***	0.26***	0.11***	0.63***
14	hazard gas station	0.07***	0.06***	-0.18***	0.03	-0.17***	-0.08***	-0.11***	-0.13***	0.22***	0.36***	0.22***	0.46***
15	hazard golf course	-0.02	-0.13***	0.11***	-0.01	0.15***	-0.07***	-0.08***	-0.02	0.17***	0.02	0.04***	0.22***
16	hazard restaurant	0.03***	0.1***	-0.2***	-0.05	-0.16***	-0.07*	-0.16***	-0.22***	0.18***	0.36***	0.14***	0.58***
17	dirt on sills	0.42***	0.16***	-0.21***	0.10***	-0.21***	-0.09***	0.05***	0.01	0.11***	0.18***	0.22***	0.06***
18	maintenance frequency	-0.34***	-0.31***	0.21***	-0.12***	0.27***	0.01	-0.10***	0.00	-0.06***	-0.13***	-0.16***	0.01
19	count of leaks	0.26***	0.18***	-0.02***	0.11***	-0.09***	0.08***	0.05***	0.06***	0.07***	0.11***	0.13***	0.02
20	odors	0.45***	0.20***	-0.2***	0.10***	-0.26***	-0.05	0.10***	0.03***	0.1***	0.13***	0.2***	-0.01***
21	surface dust	0.42***	0.12***	-0.12***	0.06***	-0.13***	-0.05***	0.07***	0.11***	0.07***	0.14***	0.19***	0.00
22	water stain	0.34***	0.19***	-0.14***	0.1***	-0.22***	-0.02	0.06***	0.02***	0.08***	0.12***	0.16***	0.05***
23	mold	0.33***	0.19***	-0.18***	0.11***	-0.26***	-0.05*	0.07***	0.02	0.1***	0.1***	0.15***	0.03***
24	meal prep frequency	-0.06***	-0.01	0.14***	0.16***	0.12***	0.11***	0.04***	0.11***	-0.05***	-0.03***	-0.02	0.02
25	smoking in house	0.26***	0.14***	-0.16***	0.04	-0.26***	-0.06***	0.08***	0.03***	0.09***	0.1***	0.18***	0.06***

****p* < 0.001 ** *p* < 0.01 **p* < 0.05

Table 3

Correlation of variables (cont.)

	13	14	15	16	17	18	19	20	21	22	23	24
14	0.68***											
15	0.23***	0.22***										
16	0.75***	0.75***	0.27***									
17	0.03	0.10***	-0.09***	0.07***								
18	0.00	-0.10***	0.13***	-0.04***	-0.49***							
19	0.03*	0.09***	-0.01	0.04***	0.31***	-0.44***						
20	-0.05***	0.08***	-0.09***	0.01	0.55***	-0.56***	0.39***					
21	-0.05***	0.04*	-0.07***	0.01***	0.6***	-0.41***	0.27***	0.44***				
22	0.04***	0.12***	-0.05***	0.05***	0.49***	-0.58***	0.54***	0.54***	0.37***			
23	0.01	0.09***	-0.06***	0.02	0.53***	-0.55***	0.39***	0.59***	0.36***	0.67***		
24	-0.01	-0.03	0.04***	-0.01	-0.09***	0.09***	0.00	-0.12***	-0.07***	-0.09***	-0.10***	
25	0.00	0.11***	-0.09***	0.02	0.3***	-0.38***	0.21***	0.33***	0.31***	0.33***	0.33***	-0.13***

***$p < 0.001$ ** $p < 0.01$ *$p < 0.05$

Results of negative binomial regression analysis

Table 4 presents the results from the negative binomial regression analysis of indoor characteristics, outdoor characteristics, and behavioral characteristics on the count of active health symptoms from the merged secondary dataset comprising responses from volunteer and paid participants. Table 4 presents the results of model 1 to model 5 of the negative binomial regression analysis. Model 1 describes the relationship between demographic characteristics and the count of active health symptoms, and this model accounts for 7% of the variance in active health symptoms. Model 2 describes the relationship between indoor characteristics and the count of active health symptoms, and this model explains 0% of the variance in active health symptoms after controlling for demographic characteristics. Model 3 describes the relationship between outdoor characteristics and the count of active health symptoms, and this model explains 3% of the variance in active health symptoms after controlling for demographic and indoor characteristics. Model 4 describes the relationship between maintenance behaviors and the count of active health symptoms, and this model explains 14% of the variance in active health symptoms after controlling for demographic, indoor, and outdoor characteristics. Model 5 describes the relationship between personal behaviors and the count of active health symptoms, and this model explains 0% of the variance in active health symptoms after controlling for demographic, indoor, outdoor characteristics, and maintenance behaviors.

In general, the findings suggest that demographic such as home ownership, outdoor characteristics, such as living close to environmental hazards, and maintenance behaviors such as taking care of leaks, surface dust, and odors explain most of the variance in number of health symptoms among home occupants.

The most salient findings are related to demographic, outdoor characteristics, and maintenance behaviors. In terms of demographic, one of the variables in model 1 (table 4) examines whether there is any difference in count of active health symptoms between volunteer and paid participants and it was found that volunteer participants were more likely to be suffering more health symptoms (β= 1.13, $p<0.05$). Also, renters were more likely to experience more health symptoms than owners (β= 0.44, $p<0.05$). In terms of outdoor characteristics (model 3), as expected, living close to hazards such as a highway (β= 0.17, $p<0.05$), an industrial area (β= 0.21, $p<0.05$), and farm (β= 0.16, $p<0.05$) are associated with more health symptoms. Noticeable dirt on sills (β= 0.44, $p<0.05$), a result of environmental hazards is also associated with more health symptoms. In terms of maintenance behaviors, issues such as leaks (β= 0.14, $p<0.05$), noticeable odor (β= 0.28, $p<0.05$), and surface dust (β= 0.34, $p<0.05$) are associated with a greater number of health symptoms.

In summary, in terms of demographics, renters are more likely to suffer more health symptoms than owners. In terms of outdoor characteristics, living close to highway, farm and industrial area are associated with more health symptoms. Environmental hazards can also affect occupants' health through the presence of dirt on sills. In terms of maintenance behaviors, issues with leaks, noticeable odors, and surface dust are associated with more health symptoms. Finally, in terms of personal behaviors, smoking is associated with more health symptoms.

Table 4

Summary of negative binomial regression analyses for indoor, outdoor, and behavioral characteristics on count of active health symptoms with merged dataset

	Count of active health symptoms				
	(1)	(2)	(3)	(4)	(5)
Demographics					
Apartment[1]	-0.09***	-0.13***	-0.16***	-0.00	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Range of year built	0.01***	0.00***	-0.00	-0.02***	-0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Square footage	0.06***	0.07***	0.09***	-0.01***	-0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Renters[2]	0.44***	0.42***	0.33***	0.15***	0.16***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
No. of people in household	0.03***	0.03***	0.01***	0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Median income by zip code	-0.00***	-0.00***	-0.00***	-0.00***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Indoor characteristics					
Garage		-0.11***	-0.11***	0.01	0.01
		(0.01)	(0.01)	(0.01)	(0.01)
Basement		-0.06***	-0.05***	0.01	0.01
		(0.01)	(0.01)	(0.01)	(0.01)
Crawlspace		0.06***	0.04***	0.02*	0.01
		(0.01)	(0.01)	(0.01)	(0.01)
Forced/central heating[3]		-0.08***	-0.05***	0.04***	0.04***
		(0.01)	(0.01)	(0.01)	(0.01)
Outdoor characteristics					
Proximity to farm			0.16***	0.10***	0.09***
			(0.01)	(0.01)	(0.01)
Proximity to airport			0.09***	0.09***	0.10***
			(0.02)	(0.02)	(0.02)
Proximity to highway			0.17***	0.11***	0.11***
			(0.01)	(0.01)	(0.01)
Proximity to industrial			0.21***	0.17***	0.16***
			(0.02)	(0.02)	(0.02)
Proximity to coffee			0.08***	0.09***	0.09***
			(0.03)	(0.03)	(0.03)
Proximity to drycleaner			0.03	0.04	0.05
			(0.03)	(0.03)	(0.03)
Proximity to gas station			0.12***	0.11***	0.10***
			(0.02)	(0.02)	(0.02)
Proximity to golf course			0.02	0.04*	0.04*
			(0.02)	(0.02)	(0.02)
Proximity to restaurant			0.05***	0.04***	0.05***
			(0.02)	(0.02)	(0.02)
Noticeable dirt on sills			0.44***	0.18***	0.18***
			(0.01)	(0.01)	(0.01)

Maintenance behaviors					
Frequency of maintenance				-0.08***	-0.07***
				(0.01)	(0.01)
Counts of leak				0.14***	0.13***
				(0.01)	(0.01)
Noticeable odors				0.28***	0.28***
				(0.01)	(0.01)
Noticeable surface dust				0.34***	0.33***
				(0.01)	(0.01)
Noticeable water stains				0.07***	0.07***
				(0.01)	(0.01)
Noticeable mold				0.02*	0.01
				(0.01)	(0.01)
Total number of pests				0.07***	0.07***
				(0.01)	(0.01)
Personal behaviors					
Total number of pets					0.03***
					(0.00)
Frequency of meal preparation					0.01
					(0.01)
Smoking indoor					0.11***
					(0.01)
Volunteer participants[4]	-1.13***	-1.08***	-1.01***	-1.06***	-1.07***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
lnalpha	0.70***	0.67***	0.61***	-0.16***	-0.17***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Constant	2.44***	2.46***	2.04***	2.27***	2.20***
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)
Observations	75,540	73,247	70,083	49,588	49,281
Deviance r-square	0.07	0.07	0.10	0.24	0.24

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

[1]Reference group for apartment is single-family home.
[2]Reference group for renter is owner.
[3]Reference group for heating system is window air conditioner, evaporative cooler, whole house fan, window fan, and no heating system.
[4]Reference group for volunteer participants is paid participants.

Results of regression with maintenance and environmental hazards factors

A second regression analysis was performed to investigate whether maintenance behaviors moderate the effect of living near environmental hazards. Polychoric factor analyses were performed to obtain a negative maintenance behaviors scale and an environmental hazards scale because some of the items in the scale are on a dichotomous scale. The items on the negative maintenance behaviors scale are leaks, noticeable odors, surface dust, water stains, molds, pests (i.e. roaches, mice, bat, termite, ant), and the factor loadings of the variables ranged between 0.28 and 0.77. The items on the environmental hazards scale are proximity to airport, highway, industrial, coffee, drycleaner, gas station, golf course, restaurant, and the factor loadings of the variables ranged between 0.28 and 0.86.

Negative maintenance is significantly associated with an increase in number of health symptoms ($\beta = 0.86$, $p < 0.05$) which means that home occupants who tend to neglect maintenance issues such as leaks, odors, surface dust, water stains, molds, and pests are more likely to exhibit more health symptoms (Table 5). Environmental hazards are also significantly associated with an increase in number of health symptoms ($\beta = 0.42$, $p < 0.05$) which means that home occupants who live near to environmental hazards are more likely to exhibit more health symptoms. An interaction between environmental hazards and negative maintenance was carried out in model 6 of the regression model (Table 5) to find out if maintenance might mitigate the effect of living near environmental hazards. However, the interaction was insignificant ($\beta = -0.11$, $p = 0.06$) which suggests that among home occupants who live near environmental hazards, there is no difference in number of health symptoms among those who engage in frequent maintenance and those who do not.

Table 5

Summary of negative binomial regression analyses with negative maintenance and environmental hazards on count of active health symptoms with merged dataset

	Count of active health symptoms					
	(1)	(2)	(3)	(4)	(5)	(6)
Demographics						
Apartment[1]	-0.09***	-0.13***	-0.15***	-0.00	-0.02	-0.02
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Range of year built	0.01***	0.00***	-0.00**	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Square footage	0.06***	0.07***	0.08***	-0.02***	-0.02***	-0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Renter[2]	0.44***	0.42***	0.32***	0.14***	0.15***	0.15***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
No. of people in household	0.03***	0.03***	0.01***	0.00	-0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Median income by zip code	-0.00***	-0.00***	-0.00***	-0.00***	-0.00***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Indoor characteristics						
Garage		-0.11***	-0.11***	0.02	0.02	0.02
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Basement		-0.06***	-0.04***	0.02**	0.02	0.02
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Crawlspace		0.06***	0.05***	0.03***	0.02**	0.02**
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Forced/central heating[3]		-0.08***	-0.05***	0.05***	0.06***	0.06***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Outdoor characteristics						
Environmental hazards[4]			0.42***	0.37***	0.38***	0.44***
			(0.02)	(0.02)	(0.02)	(0.05)
Noticeable dirt on sills			0.46***	0.25***	0.24***	0.24***
			(0.01)	(0.01)	(0.01)	(0.01)
Maintenance behaviors						
Negative maintenance[5]				0.86***	0.82***	0.84***
				(0.01)	(0.01)	(0.02)

Personal behaviors						
Total number of pets					0.04***	0.04***
					(0.00)	(0.00)
Frequency of meal preparation					0.02**	0.02**
					(0.01)	(0.01)
Smoking indoor					0.13***	0.13***
					(0.01)	(0.01)
Volunteer participants[6]	-1.13***	-1.08***	-1.02***	-1.10***	-1.11***	-1.12***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Negative maintenance*Environmental hazards						-0.11**
						(0.06)
lnalpha	0.70***	0.67***	0.62***	-0.11***	-0.12***	-0.12***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Constant	2.44***	2.46***	2.18***	2.33***	2.26***	2.25***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)
Observations	75,540	73,247	70,083	49,888	49,577	49,577
Deviance r-square	0.07	0.07	0.10	021	0.22	0.22

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

[1]Reference group for apartment is single-family home.
[2]Reference group for renter is owner.
[3]Reference group for heating system is window air conditioner, evaporative cooler, whole house fan, window fan, and no heating system.
[4]Environmental hazards: proximity to airport, highway, industrial, coffee, drycleaner, gas station, golf course, restaurant
[5]Negative maintenance: leaks, noticeable odors, surface dust, water stains, molds, pests (i.e. roaches, mice, bat, termite, ant)
[6]Reference group for volunteer participants is paid participants.

Robustness check

A robustness check was performed to compare the responses of the paid participants to those of the volunteer participants are comparable. Comparison of analyses results as a check of robustness have been documented in previous studies (Pellegrini, 2011; Vuong et al., 2021). A notable difference is that paid participants reported experiencing more health symptoms than volunteer participants which suggests that there might be other characteristics that differentiate them. Despite the difference in number of health symptoms experienced by both groups of participants, the variance in count of active health symptoms as explained by indoor, outdoor, and behavioral characteristics are consistent across both datasets. In both datasets, maintenance behaviors explained the greatest variance in count of active health symptoms, 9% in the dataset with responses from paid participants, and 7% in the dataset with responses from volunteer participants. Other than maintenance behaviors, outdoor characteristics also explained a sizable variability in count of active health symptoms, 6% in the dataset with responses from paid participants, and 3% in the dataset with responses from volunteer participants, followed by demographics which explained 3% in the dataset with responses from paid participants, and 2% in the dataset with responses from volunteer participants.

The dataset with responses from the volunteer participants contains more variables than the dataset with responses from the paid participants. The additional variables in the volunteer participants dataset provide useful insights into the effects of beneficial and harmful behaviors such as the presence of carpet, frequency of vacuuming, and the use of air purifier on health symptoms. A deeper investigation into the role of these variables in mitigating or worsening indoor and outdoor characteristics, and thereby health symptoms was explored through structural equation modeling and is presented in the next section.

Results of structural equation modeling (SEM)

I fitted a SEM model to investigate the behaviors that can mitigate and worsen outdoor characteristics, maintenance behaviors, and personal behaviors with health symptoms as the outcome (Table 6 and Figure 7). The model fit for the SEM model is $\chi 2(93, N = 85{,}442) = 49148.68$, $p < .05$; RMSEA (90% confidence interval) = .076 (.076 – .077).

In terms of maintenance behaviors, I investigated two hypotheses: the relationship between leaks and counts of active health symptoms, and the relationship between frequent long shower and count of active health symptoms. Leaks are associated with an increase in health symptoms ($\beta = .13$, $p <.001$), leaks are also associated with an increase in water stains ($\beta = .39$, $p <.001$), and water stains are associated with an increase in mold ($\beta = .43$, $p <.001$), and mold is associated with an increase in health symptoms ($\beta = .09$, $p <.001$). Taking frequent long shower is also associated with an increase in mold ($\beta = .04$, $p <.001$) although turning on the bathroom fan helps to reduce mold ($\beta = -.04$, $p <.001$). Living in older home is also associated with having more leaks ($\beta = .16$, $p <.001$). In conclusion, the hypotheses that leaks and frequent long shower result in an increase in mold and that the use of a bathroom exhaust can reduce mold growth are supported.

In terms of personal behaviors, I investigated the hypotheses that smoking and the presence of carpet result in an increase in surface dust, resulting in an increase in the number of health symptoms. Smoking indoor can result in the accumulation of surface dust ($\beta = .16$, $p <.001$) and is associated with more health symptoms ($\beta = .11$, $p <.001$). The presence of carpet is linked to an increase in surface dust ($\beta = .06$, $p <.001$). Surface dust is related to an increase in health symptoms ($\beta = .15$, $p <.001$), though frequent vacuuming helps to reduce surface dust ($\beta = -.02$, $p <.001$) and health symptoms ($\beta = -.12$, $p <.001$). In conclusion, the hypotheses that smoking indoor and the presence of a carpet could result in more surface dust and health symptoms, and that frequent vacuuming can mitigate the effect of surface dust on health symptoms are supported.

In terms of outdoor characteristics, I investigated the hypotheses that living near environmental hazards result in an increase in dirt on windowsills which results in an increase in the number of health symptoms, and the use of an air purifier can mitigate the effect of dirt on windowsills. Living near environmental hazards is associated with an increase in health symptoms ($\beta = .09$, $p < .001$). Environmental hazards are also related to an increase in dirt on sills ($\beta = .14$, $p < .001$), and that results in an increase in health symptoms ($\beta = .17$, $p < .001$). Home occupants who live near environmental hazards are also more likely to use an air purifier ($\beta = .03$, $p < .001$). However, the use of air purifier is associated with more health symptoms ($\beta = .05$ $p < .001$) which suggests that the usage of air purifier might be detrimental to health or those home occupants with more health symptoms are more likely to use an air purifier. The opening of window is associated with fewer health symptoms ($\beta = -.02$ $p < .001$); however, the positive relationship between the opening of window and environmental hazards ($\beta = .02$ $p < .001$) suggests that it might not be a good idea to open the window if one lives near environmental hazards. In conclusion, the hypothesis that living close to environmental hazards results in an increase in dirt on windowsills and result in more health symptoms is supported; however, the use of an air purifier to mitigate the effect of living near environmental hazards is not supported because the use of an air purifier leads to more health symptoms.

In summary, the SEM illustrates the behaviors that can worsen or mitigate the maintenance behaviors, personal behaviors, and outdoor characteristics. The choice of maintenance behaviors, personal behaviors, and outdoor characteristics to include in the SEM was guided by the regression results. The findings of the regression analysis were useful in that it illuminated the types of maintenance behaviors, personal behaviors, and outdoor characteristics that were associated with more health symptoms. However, it did not provide insight on the behaviors that home occupants could take to mitigate the negative effects of maintenance behaviors, personal behaviors, and outdoor characteristics. The SEM findings added value by clarifying the causal relationships between the observed variables in maintenance behaviors, personal behaviors, and outdoor characteristics, and help shed light on behaviors that home occupants could adopt to reduce the count of active health symptoms.

Table 6

Results of the Structural Equation Model

Antecedent variable → Consequent variable	Regression weight	Standard error	Critical ratio	*P* value	Standardized regression weight
Maintenance behaviors					
Range of year built → Count of active leaks	0.04	0.001	42.46	***	0.16
Count of active leaks → Noticeable water stains	0.25	0.002	109.50	***	0.39
Count of active leaks → Noticeable mold stains	0.05	0.002	23.25	***	0.09
Noticeable water stains → Noticeable mold stains	0.40	0.003	129.16	***	0.43
Frequency of long shower → Noticeable mold stains	0.03	0.002	11.52	***	0.05
Frequency of long shower → All bathroom fans exhaust outside	0.02	0.003	7.80	***	0.03
All bathroom fans exhaust outside → Noticeable mold stains	-0.03	0.003	-11.20	***	-0.04
Noticeable mold stains → Count of active health symptoms	1.00	0.04	26.88	***	0.09
Count of active leaks → Count of active health symptoms	0.86	0.03	34.59	***	0.13
Personal behaviors					
Smoking indoor → Noticeable surface dust	0.21	0.005	45.00	***	0.16
Smoking indoor → Count of active health symptoms	1.37	0.04	31.00	***	0.11
Presence of carpet in the house → Noticeable surface dust	0.07	0.003	19.04	***	0.06
Presence of carpet in the house → Vacuum frequency	0.06	0.01	5.35	***	0.02

Vacuum frequency → Noticeable surface dust	-0.01	0.001	-5.70	***	-0.02
Noticeable surface dust → Count of active health symptoms	1.48	0.03	45.22	***	0.15
Vaccum frequency → Count of active health symptoms	-0.40	0.01	-33.23	***	-0.12
Windows are open → Count of active health symptoms	-0.22	0.03	-6.32	***	-0.02
Air purifier → Count of active health symptoms	0.70	0.04	16.01	***	0.05
Smoking indoor ↔ Median income by zip code	-1082.12	29.48	-36.71	***	-0.13
Windows are open ↔ Median income by zip code	1140.08	39.72	28.70	***	0.11
Outdoor characteristics					
Environmental hazards → Noticeable dirt on sills	0.06	0.001	41.88	***	0.14
Environmental hazards → Air purifier	0.08	0.001	7.59	***	0.03
Environmental hazards → Noticeable surface dust	0.05	0.001	36.56	***	0.12
Environmental hazards → Count of active health symptoms	0.38	0.01	28.71	***	0.09
Noticeable dirt on sills → Count of active health symptoms	1.62	0.03	50.97	***	0.17
Windows are open ↔ Environmental hazards	0.01	0.002	6.10	***	0.02
Control relationships					
Median income by zip code ↔ Environmental hazards	-1339.93	84.32	-15.89	***	-0.06
Median income by zip code ↔ Range of year built	-8811.68	220.49	-39.96	***	-0.14

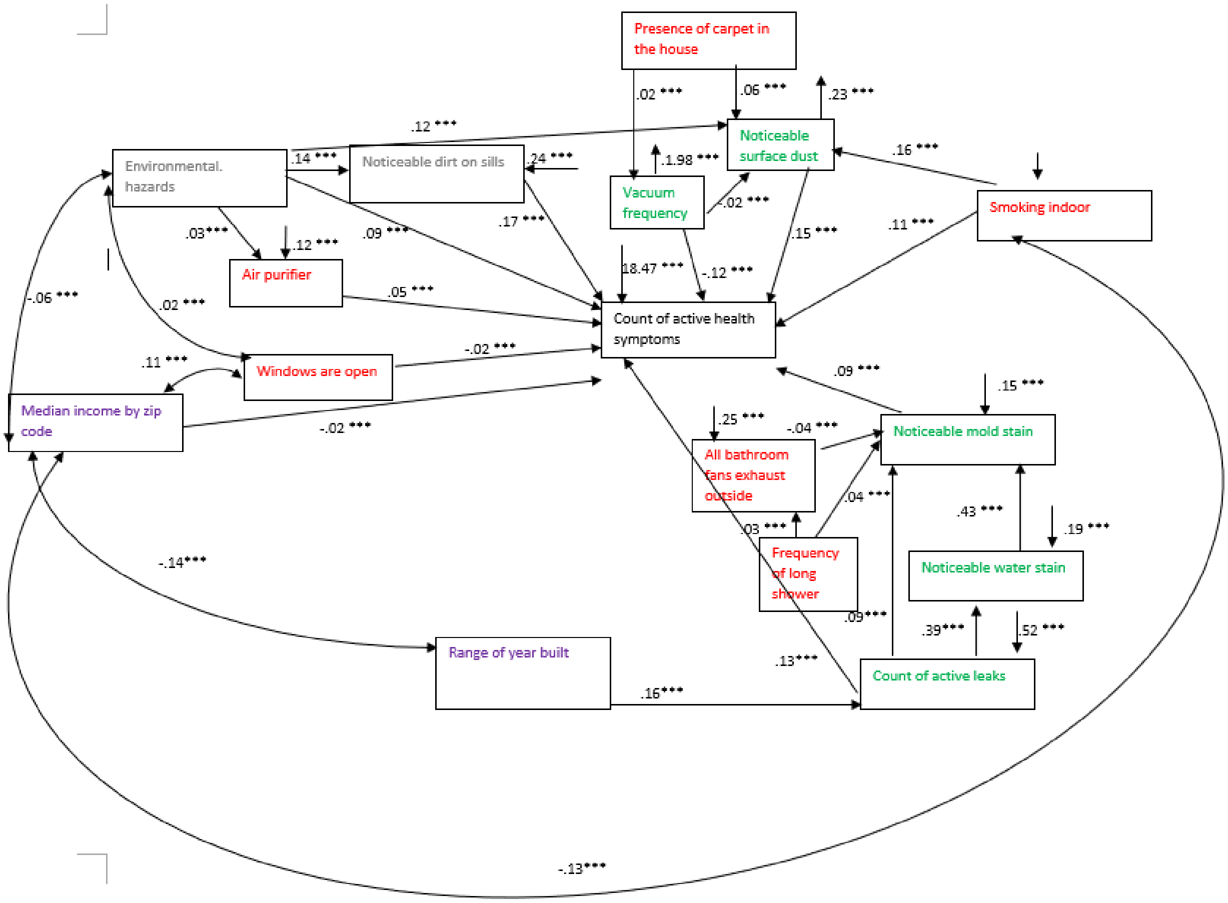

Figure 7. Structural equation model of active health symptoms with standardized estimate

Note: *** *p*<.001 ** *p*<.01. Environmental hazards: farm, airport, highway, industrial, coffee place, dry cleaner, gas station, golf course, restaurant. Color-coded: Environmental hazards, maintenance behaviors, personal behaviors, housing/demographic.

Discussion

Summary of Results

In this study, I set out to investigate the contribution of indoor, outdoor, and behavioral characteristics in explaining the variability in health symptoms, and to identify if there are any mitigating behaviors that can result in a reduction in health symptoms.

Based on 83,289 survey responses, I found that demographics, outdoor characteristics, and maintenance behaviors explain the greatest variability in the number of health symptoms that home occupants experienced.

In terms of demographic, renters are likely to suffer more health symptoms than owners because they are more likely to live near hazardous sites and have lower income (Chakraborty, 2012; Giordano & Cheever, 2010).

In terms of outdoor characteristics, previous research found that the relationship between indoor and outdoor pollutant concentrations is 75% (Leung, 2015b); however, those research did not quantify the effect of outdoor characteristics on home occupants' health. My research addresses this gap by quantifying the variability in active health symptoms that are explained by outdoor characteristics. In terms of outdoor characteristics, I identified environmental hazards such as living near the highway and industrial area as significantly associated with a greater number of health symptoms and this is in line with those of previous studies (Awasthi et al., 2013; Dong et al., 2013; L. Li et al., 2015; Mustapha et al., 2011). While I found that the opening of window results in fewer health symptoms, the positive relationship suggests that opening of window might be detrimental for home occupants who live near environmental hazards.

In terms of maintenance behaviors, I found that leaks, noticeable odor, and surface dust are significantly related to an increase in health symptoms and my finding is similar to what has been found by previous studies regarding the relationship between leaks (Massey et al., 2012), noticeable odor (A. Li et al., 2014; Lin et al., 2014; Norbäck et al., 2014; Wang et al., 2013), surface dust (Dhabadi et al., 2012; Ghozikali et al., 2018), and health. While earlier studies provided insights into the maintenance behaviors that can affect health, they did not quantify the impact of maintenance behaviors on health. This study addresses the gap by quantifying the variability in active health symptoms that are explained by maintenance behaviors.

As a follow-up to the regression analysis, I performed SEM to understand the behaviors that can ameliorate the impact of negative environmental hazards and maintenance behaviors on health symptoms. Previous studies have identified mold and home dampness such as leaks as factors that contribute to respiratory conditions (Jaakkola et al., 2013), and that the use of a bathroom exhaust fan can control moisture and reduce mold growth (Lopez-Arce et al., 2020a). However, those studies did not establish the relationship between the behavior of using a bathroom exhaust fan, mold growth, and health symptoms. This study fills this gap by identifying the behaviors that contribute to and ameliorate mold growth. I found that leak affects health by resulting in an increase in water stains and molds. I also found that living in an older home is linked to an increase in leaks. Taking frequent long showers is also associated with an increase in molds; however, the use of a bath fan can ameliorate that.

In terms of personal behaviors, as expected I found that smoking indoor is associated with more health symptoms. Earlier studies have found that passive smoking is associated with more respiratory issues in children (Butz et al., 2011; Hill & Liang, 2008) and that PAH (Hoh et al., 2012) and nicotine (Matt et al., 2004) are detected in the house dust of occupants who smoke.

However, those studies did not quantify the relationship between smoking indoor and the presence of house dust, and the impact that house dust has on health. Those studies also did not discuss what home occupants can do to mitigate the impact of house dust, such as through behaviors such as smoking, and vacuuming. In this study, I examined the impact of surface dust on health symptoms, as well as the direct effect that smoking has on health symptoms, as well as the indirect effect that smoking has through an increase in surface dust. I also found that carpet is a contributor of surface dust and frequent vacuuming is associated with a reduction in health symptoms. Frequent vacuuming works because it can remove endotoxin and airborne glucan that are found in surface dust (Salares et al., 2009). A carpet is also a site for allergen-causing dust mite and dust and vacuuming can help to eliminate the presence of these allergens (Roberts et al., 1999). This study extends the connection between vacuuming and surface dust by investigating the connection between vacuuming and health outcomes highlighting the beneficial effect of vacuuming on health symptoms.

Limitations

One of the limitations of this study is that volunteer participants were motivated to participate because they probably were more likely to experience issues in their homes and/or experienced health symptoms, and this might affect the generalizability of the findings. To mitigate the effect of an unrepresentative sample, similar analyses were conducted with both the volunteer participants and the more representative paid participants (Appendix B). The variability in health outcomes explained by indoor, outdoor, and behavioral characteristics were similar across both groups of participants, and in both groups, demographics, outdoor characteristics, and maintenance behaviors were found to be the greatest contributors to health outcomes. While it is not possible to account fully for the bias that might occur with the volunteer participants, the study findings can still benefit individuals, especially those with health conditions who are interested in behaviors that can mitigate the impact of poor indoor air quality. Future studies should be conducted with a more representative population, thus avoiding the problem of self-selection to examine if the contribution of outdoor characteristics and maintenance behaviors to health symptoms is similar to what was found in this study. Subsequent studies should also investigate if the effect of living near environmental hazards and maintenance issues such as leaks are just as deleterious among healthy individuals, and whether the moderating behaviors highlighted in the study findings can mitigate their negative effect on health. The recruitment of volunteer participants who are likely to experience more issues in their homes and/or experienced more health issues are also likely to influence some of the study findings, for instance the use of air purifier were found to result in more health symptoms. It could be the case that participants who had more health symptoms were more likely to use air purifier.

Another limitation of this study is that the data from this study were obtained from participants' self-reported surveys which could result in issues such as social desirability, difficulty with retrieval, and judgment with a self-reported survey (Podsakoff et al., 2003). Social desirability occurs when participants are inclined to respond to survey questions so that they will be viewed in a favorable light, for instance downplaying the negative issues in their homes or the number of health symptoms that they experienced. Problem with retrieval occurs when participants must recall instances, for example, participants might not be accurate in their recall of the frequency of meal preparation. Problem with judgment occurs when the participants face an issue matching the recalled instances to the scale context. For instance, the options in the frequency of maintenance question were deferred maintenance, somewhat maintained, and highly maintained; however, participants might have a different interpretation of what constitutes highly maintained and somewhat maintained and recalled instances might map differently across participants.

The final limitation has to do with the fact that all the models in the regression analysis could only explain 24% of the variance in active health symptoms (Table 4). The moderate variance explained by the models is not surprising as health outcomes are affected by a multitude of factors, beyond what was covered in the survey. Other than the factors described in the survey, health outcomes can also be affected by diet and exercise, use of alcohol and drugs, quality of clinical care, education attainment, employment status, family and social support, and community safety (Hood et al., 2016).

Conclusions

In this study, I set out to investigate the contribution of indoor, outdoor, and behavioral characteristics on health symptoms, as well as identify the behaviors that worsen or mitigate indoor air quality with health as the outcome.

I found that demographics, outdoor characteristics, and maintenance behaviors account for the greatest variance in health symptoms. While the variance in heath symptoms explained by demographic, indoor, outdoor, and behavioral characteristics stand at only 14%, this is unavoidable given that health outcomes are affected by other factors which are not measured in the survey (Hood et al., 2016). I also identified behaviors through SEM that can worsen or mitigate the impact of maintenance behaviors and outdoor characteristics. In the next few sections, I address recommendations concerning the study key findings.

Renters are more likely to live near hazardous sites and this might be due to the lack of information about the presence of hazardous sites. The EPA Superfund program was created to clean up hazardous sites and provide residents information about hazardous sites near their homes. However, renters are less likely to be aware that they are living near hazardous sites and there is no legal obligation for landlords to inform their tenants. Also renters are less likely to participate in neighborhood activism and that preclude them from learning more about their neighborhood (Rhubart & Galli Robertson, 2020). The first step to this information asymmetry might be to make it a requirement for tenants to be informed of hazardous sites in the proximity before they rent a place.

The lack of maintenance can result in more health symptoms because leaks can escalate to water stains, and finally molds. This highlights the importance for home occupants to engage in periodic maintenance and to not let an issue escalate from leaks to water stains. While regular maintenance is beneficial to home occupants' well-being, renters are less inclined to engage in periodic maintenance due to the transient nature of renting and the lack of financial incentive (Dietz & Haurin, 2003). There are currently no requirements for landlord to reimburse tenants for maintenance that are carried out by the tenants. Instead of viewing it as a financial liability, landlords could view it as part and parcel of upkeep for the home, and that regular maintenance work is cheaper than repair work due to deferred maintenance. As periodic maintenance is also beneficial to health outcomes, the state could encourage renters to perform home maintenance by passing a legislature under the tenant protection clause to hold landlord accountable for the financial costs of home maintenance and upkeep.

Home occupants who live near environmental hazards are more likely to use air purifier; however, I found that the use of air purifier is associated with more health symptoms. Some air purifiers are known to produce ozone during operation although the results are mixed (Britigan et al., 2006; Cestonaro et al., 2017). When it comes to the impact of ozone-generating air purifier, it might be better to err on the side of caution and only use an air purifier that does not produce ozone. It could also be the case that home occupants who are experiencing more health symptoms are inclined to use an air purifier.

Appendix A

Table A1

Description of variables from merged dataset

Variable	Type	Categories
Demographics		
State	Categorical	
Indoor characteristics		
Ownership	Categorical	Own; rent; military
Building type	Categorical	Single family; detached, Multi-unit high-rise (> 3 stories); Mobile/manufactured home; Multi-unit low-rise (< 3 stories)
Range of year home was built	Ordinal	1 2015 to present; 2 2010 to 2014; 3 2005 to 2009; 4 2000 to 2004; 5 1990 to 1999; 6 1980 to 1989; 7 1970 to 1979; 8 1960 to 1969; 9 1950 to 1959; 10 1940 to 1949; 11 1930 to 1939; 12 1920 to 1929; 13 Before 1919
Square footage	Ordinal	1 Less than 850; 2 850 to 1100, 3-1101 to 1800; 4 1801 to 2800; 5 2801 to 3500; 6 3501 to 5000; 7 5001 to 7000; 8 Greater than 7000
Heating system	Categorical	forced/central heat; baseboard radiant floor; wood stove/fireplace; radiator; none; wall heater/furnace; floor furnace
Count of active leaks	Binary	Leak 1 – no leak, minor/moderate/major leak; leak 2 – no leak, minor/moderate/major leak
Noticeable odors	Binary	False; true
Noticeable surface dust	Binary	False; true
Noticeable water stains	Binary	False; true
Noticeable mold	Binary	False; true
Maintenance level	Ordinal	Expertly/well maintained; Somewhat maintained; Deferred maintenance

Variable	Type	Categories
Roaches	Binary	False; true
Mice	Binary	False; true
Bat	Binary	False; true
Termite	Binary	False; true
Ant	Binary	False; true
Outdoor characteristics		
Noticeable dirt on sills	Binary	False; true
Hazard farm	Binary	False; true
Hazard airport	Binary	False; true
Hazard highway	Binary	False; true
Hazard industrial	Binary	False; true
Hazard wood smoke	Binary	False; true
Hazard gas station	Binary	False; true
Hazard wetlands	Binary	False; true
Hazard ocean	Binary	False; true
Hazard coffee	Binary	False; true
Hazard drycleaner	Binary	False; true
Hazard golf course	Binary	False; true
Hazard restaurant	Binary	False; true
Behavioral characteristics		
Number of pets	Continuous	0 to 7 or more
Meal prep weekly	Ordinal	9 or fewer meals per week, 10 or more meals per week, none of the above
Smoking in the house	Binary	False; true
Dependent variable		
Number of active health symptoms	Continuous	

Table A2

Summary statistics of variables from merged dataset

Variable	N	Mean	SD.	Min	Max
Demographics					
Ownership					
Owner	82,839	.61	.49	0	1
Renter	82,839	.39	.49	0	1
Housing type					
Single, family detached	85,502	.65	.48	0	1
Multi-unit low-rise	85,502	.07	.26	0	1
Multi-unit high-rise	85,502	.09	.28	0	1
Mobile home	85,502	.19	.39	0	1
Range of year built	84,498	6.9	2.96	1	13
Square footage	83,752	3.04	1.33	1	8
Indoor characteristics					
Garage	90,202	.32	.47	0	1
Basement	90,202	.33	.47	0	1
Crawlspace	90,202	.28	.45	0	1
Heating type					
Forced/central heat	83,585	.69	.46	0	1
Baseboard	83,585	.08	.27	0	1
Radiant floor	83,585	.01	.12	0	1
Wood stove/fireplace	83,585	.03	.16	0	1
Radiator	83,585	.05	.21	0	1
None	83,585	.08	.27	0	1
Floor furnace	83,585	.03	.16	0	1
Outdoor characteristics					
Proximity to farm	90,202	.22	.42	0	1
Proximity to airport	90,202	.04	.21	0	1
Proximity to highway	90,202	.48	.5	0	1
Proximity to industrial	90,202	.06	.24	0	1
Proximity to coffee	90,202	.03	.18	0	1
Proximity to drycleaner	90,202	.04	.18	0	1
Proximity to gas station	90,202	.12	.33	0	1
Proximity to golf course	90,202	.04	.19	0	1
Proximity to restaurant	90,202	.12	.33	0	1
Noticeable dirt on sills	85,690	.43	.49	0	1
Maintenance behaviors					
Frequency of maintenance	85,113	2.07	.72	1	3
Counts of leak	64,717	.72	.73	0	2
Noticeable odors	87,166	.49	.5	0	1
Noticeable surface dust	85,963	.61	.49	0	1
Noticeable water stains	85,998	.32	.47	0	1
Noticeable mold	85,988	.26	.44	0	1
Pests					
Roaches	90,202	.17	.37	0	1
Mice	90,202	.2	.4	0	1
Bats	90,202	.01	.11	0	1
Termites	90,202	.04	.19	0	1
Ants	90,202	.3	.46	0	1
Personal behaviors					
No. of pets	91,081	1.31	1.55	0	6
Cooking frequency	88,725	1.93	.74	1	3

Smoking indoor	77,243	.17	.38	0	1
Dependent variable					
Count of active health symptoms	90,202	4.11	5.03	0	23

Table A3

Description of variables from volunteer participants survey

Variable	Type	Categories
Demographics		
State	Categorical	
Indoor characteristics		
Ownership	Categorical	Own; rent; military
Building type	Categorical	Single family; detached, Multi-unit high-rise (> 3 stories); Mobile/manufactured home; Multi-unit low-rise (< 3 stories)
Storey	Continuous	
Range of year home was built	Ordinal	1 2015 to present; 2 2010 to 2014; 3 2005 to 2009; 4 2000 to 2004; 5 1990 to 1999; 6 1980 to 1989; 7 1970 to 1979; 8 1960 to 1969; 9 1950 to 1959; 10 1940 to 1949; 11 1930 to 1939; 12 1920 to 1929; 13 Before 1919
Square footage	Ordinal	1 Less than 850; 2 850 to 1100, 3-1101 to 1800; 4 1801 to 2800; 5 2801 to 3500; 6 3501 to 5000; 7 5001 to 7000; 8 Greater than 7000
Brick cladding	Binary	False; true
Vinyl cladding	Binary	False; true
Wood cladding	Binary	False; true
Stucco cladding	Binary	False; true
Concrete cladding	Binary	False; true
Cement cladding	Binary	False; true
Stone cladding	Binary	False; true
Fireplace type	Categorical	None; sealed; open wood
Heating system	Categorical	forced/central heat; baseboard radiant floor; wood stove/fireplace; radiator; none; wall heater/furnace; floor furnace

Variable	Type	Categories
Cooling system	Categorical	forced air/central air conditioning; window air conditioner; evaporative cooler; whole house fan; window fan; none; fan/ceiling fan
Count of active leaks	Continuous	
Noticeable odors	Binary	False; true
Noticeable surface dust	Binary	False; true
Noticeable water stains	Binary	False; true
Noticeable mold	Binary	False; true
Maintenance level	Ordinal	Expertly/well maintained; Somewhat maintained; Deferred maintenance
Roaches	Binary	False; true
Mice	Binary	False; true
Bat	Binary	False; true
Termite	Binary	False; true
Mite	Binary	False; true
Ant	Binary	False; true
Outdoor characteristics		
Noticeable dirt on sills	Binary	False; true
Hazard farm	Binary	False; true
Hazard airport	Binary	False; true
Hazard highway	Binary	False; true
Hazard industrial	Binary	False; true
Hazard wood smoke	Binary	False; true
Hazard gas station	Binary	False; true
Hazard wetlands	Binary	False; true
Hazard ocean	Binary	False; true
Hazard coffee	Binary	False; true
Hazard drycleaner	Binary	False; true
Hazard golf course	Binary	False; true
Hazard restaurant	Binary	False; true
Humidity	Categorical	Dry; humid; marine

Variable	Type	Categories
Behavioral characteristics		
Number of dogs	Continuous	
Number of cats	Continuous	
Windows open	Binary	False; true
Meal prep weekly	Ordinal	0 to 4; 5 to 10; 11 or more
Use unvented hood while cooking	Binary	False; true
Frequency of long shower	Ordinal	Never; 1 to 5 times per week; 6+ times per week
Frequently run bath fan when showering	Binary	False; true
Fireplace use	Ordinal	Never; seldom; often
Vacuum frequency	Ordinal	Rarely; monthly; 1x per week; 2x per week; 3x per week; daily
Chemical storage cleaning supplies- bedroom	Binary	False; true
Chemical storage cleaning supplies- inside the house	Binary	False; true
Chemical storage cleaning supplies- attachment to the house	Binary	False; true
Chemical storage cleaning supplies- detachment to the house	Binary	False; true
Chemical storage grooming supplies- bedroom	Binary	False; true

Variable	Type	Categories
Chemical storage grooming supplies- inside the house	Binary	False; true
Chemical storage grooming supplies- attachment to the house	Binary	False; true
Chemical storage grooming supplies- detachment to the house	Binary	False; true
Chemical storage art supplies- bedroom	Binary	False; true
Chemical storage art supplies- inside the house	Binary	False; true
Chemical storage art supplies- attachment to the house	Binary	False; true
Chemical storage art supplies- detachment to the house	Binary	False; true
Chemical storage gardening supplies- bedroom	Binary	False; true
Chemical storage gardening supplies- inside the house	Binary	False; true
Chemical storage gardening supplies- attachment to the house	Binary	False; true
Chemical storage gardening supplies- detachment to the house	Binary	False; true

Variable	Type	Categories
Shoes removed	Binary	False; true
Smoking in the house	Binary	False; true
House is scented	Binary	False; true
Dependent variable		
Number of active health symptoms	Continuous	

Table A4

Summary statistics of variables from volunteer participants survey

Variable	N	Mean	SD.	Min	Max
Demographics					
Storey	68,307	1.68	0.81	1	4
Range of year built	68,348	6.95	2.89	1	13
Square footage	67,854	2.95	1.29	1	8
Maintenance level	68,904	2.00	0.72	1	3
Cladding					
Brick	70,393	0.30	0.46	0	1
Vinyl	70,393	0.33	0.47	0	1
Wood	70,393	0.26	0.44	0	1
Stucco	70,393	0.14	0.35	0	1
Concrete	70,393	0.07	0.25	0	1
Cement	70,393	0.05	0.21	0	1
Stone	70,393	0.03	0.18	0	1
Adobe	70,393	0	0.06	0	1
Garage	70,393	0.32	0.47	0	1
Basement	70,393	0.34	0.47	0	1
Crawlspace	70,393	0.30	0.46	0	1
Slab	58,486	0.27	0.45	0	1
Fireplace type					
Never	70,393	0.68	0.47	0	1
Sealed	70,393	0.06	0.24	0	1
Open	70,393	0.07	0.25	0	1
Wood	70,393	0.20	0.40	0	1
Heating system					
Forced / central heat	69,263	0.69	0.46	0	1
Baseboard	69,263	0.08	0.27	0	1
Radiant floor	69,263	0.01	0.12	0	1
Wood stove / Fireplace	69,263	0.03	0.16	0	1
None	69,263	0.05	0.21	0	1
Wall heater / Furnace	69,263	0.08	0.26	0	1
Floor furnace	69,263	0.03	0.16	0	1
Cooling system					
Forced air / Central AC	69,477	0.66	0.47	0	1
Window AC	69,477	0.19	0.39	0	1
Evaporative Cooler	69,477	0.02	0.12	0	1
Whole-house fan	69,477	0.01	0.07	0	1
Window fan	69,477	0.03	0.17	0	1
None	69,477	0.07	0.26	0	1
Portable fan/ceiling fan	69,477	0.02	0.15	0	1
Count of active leaks	50,074	0.83	0.90	0	5
Noticeable odors	67,716	0.58	0.49	0	1
Noticeable surface	66,511	0.69	0.46	0	1

Variable	N	Mean	SD.	Min	Max
dust					
Noticeable water stains	66,542	0.38	0.49	0	1
Noticeable mold	66,554	0.31	0.46	0	1
Roaches	70,393	0.19	0.40	0	1
Mice	70,393	0.22	0.42	0	1
Bat	70,393	0.01	0.12	0	1
Termite	70,393	0.04	0.20	0	1
Mite	70,393	0.03	0.17	0	1
Ant	70,393	0.34	0.47	0	1
Outdoor characteristics					
Noticeable dirt on sills	66,251	0.51	0.50	0	1
Hazard farm	70,393	0.23	0.42	0	1
Hazard airport	70,393	0.05	0.22	0	1
Hazard highway	70,393	0.51	0.50	0	1
Hazard industrial	70,393	0.07	0.25	0	1
Hazard wood smoke	70,393	0.11	0.31	0	1
Hazard gas station	70,393	0.11	0.32	0	1
Hazard wetlands	70,393	0.16	0.36	0	1
Hazard ocean	70,393	0.03	0.16	0	1
Hazard coffee	70,393	0.03	0.17	0	1
Hazard drycleaner	70,393	0.03	0.16	0	1
Hazard golf course	70,393	0.04	0.19	0	1
Hazard restaurant	70,393	0.10	0.31	0	1
Hazard wetlands	70,393	0.16	0.36	0	1
Hazard ocean	70,393	0.03	0.16	0	1
Hazard coffee place	70,393	0.03	0.17	0	1
Hazard drycleaner	70,393	0.03	0.16	0	1
Hazard golf course	70,393	0.04	0.19	0	1
Hazard restaurant	70,393	0.10	0.31	0	1
Humidity					
Dry	69,232	0.15	0.36	0	1
Humid	69,232	0.79	0.41	0	1
Marine	69,232	0.06	0.23	0	1
Behavioral factors					
Number of dogs	58,806	0.50	1.03	0	6
Number of cats	58,806	0.76	1.05	0	6
Windows open	69,413	2.47	0.73	1	4
Meal prep weekly	69,233	1.93	0.73	1	3
Use unvented hood while cooking	67,221	0.33	0.47	0	1
Frequency of long shower	63,396	2.22	0.69	1	3
Frequently run bath fan when showering	67,923	0.19	0.40	0	1
Fireplace use					
Never	70,393	0.69	0.46	0	1

Variable	N	Mean	SD.	Min	Max
Seldom	70,393	0.26	0.44	0	1
Often	70,393	0.05	0.22	0	1
Vacuum frequency	69,294	3.76	1.41	1	6
Chemical storage cleaning supplies					
Bedroom	70,393	0.03	0.17	0	1
Inside the house	70,393	0.53	0.50	0	1
Attachment to the house	70,393	0.19	0.39	0	1
			0		
Detachment to the house	70,393	0.20	0.40	0	1
Chemical storage grooming supplies					
Bedroom	70,393	0.31	0.46	0	1
Inside the house	70,393	0.64	0.48	0	1
Attachment to the house	70,393	0.02	0.12	0	1
Detachment to the house	70,393	0.01	0.10	0	1
Chemical storage art supplies					
Bedroom	70,393	0.04	0.20	0	1
Inside the house	70,393	0.27	0.44	0	1
Attachment to the house	70,393	0.25	0.43	0	1
Detachment to the house	70,393	0.17	0.38	0	1
Chemical storage gardening supplies					
Bedroom	70,393	0	0.06	0	1
Inside the house	70,393	0.07	0.25	0	1
Attachment to the house	70,393	0.22	0.41	0	1
Detachment to the house	70,393	0.35	0.48	0	1
Shoes removed	57,838	0.39	0.49	0	1
Smoking in the house	57,822	0.20	0.40	0	1
House is scented	57,622	0.67	0.47	0	1
Dependent variable					
Number of active health symptoms	70,393	4.73	5.17	0	23

N: Number of observation Min: Minimum Max: Maximum
SD: Standard deviation

Table A5

Description of variables from paid volunteers' survey

Variable	Type	Categories
Demographics		
State	Categorical	
Indoor characteristics		
Ownership	Categorical	Own; rent; military
Building type	Categorical	Single family; detached, Multi-unit high-rise (> 3 stories); Mobile/manufactured home; Multi-unit low-rise (< 3 stories)
Range of year home was built	Ordinal	1 2015 to present; 2 2010 to 2014; 3 2005 to 2009; 4 2000 to 2004; 5 1990 to 1999; 6 1980 to 1989; 7 1970 to 1979; 8 1960 to 1969; 9 1950 to 1959; 10 1940 to 1949; 11 1930 to 1939; 12 1920 to 1929; 13 Before 1919
Square footage	Ordinal	1 Less than 850; 2 850 to 1100, 3-1101 to 1800; 4 1801 to 2800; 5 2801 to 3500; 6 3501 to 5000; 7 5001 to 7000; 8 Greater than 7000
Heating system	Categorical	forced/central heat; baseboard radiant floor; wood stove/fireplace; radiator; none; wall heater/furnace; floor furnace
Count of active leaks	Binary	Leak 1 – no leak, minor/moderate/major leak; leak 2 – no leak, minor/moderate/major leak
Noticeable odors	Binary	False; true
Noticeable surface dust	Binary	False; true
Noticeable water stains	Binary	False; true
Noticeable mold	Binary	False; true
Maintenance level	Ordinal	Expertly/well maintained; Somewhat maintained; Deferred maintenance
Roaches	Binary	False; true
Mice	Binary	False; true
Bat	Binary	False; true

Variable	Type	Categories
Termite	Binary	False; true
Ant	Binary	False; true
Outdoor characteristics		
Noticeable dirt on sills	Binary	False; true
Hazard farm	Binary	False; true
Hazard airport	Binary	False; true
Hazard highway	Binary	False; true
Hazard industrial	Binary	False; true
Hazard wood smoke	Binary	False; true
Hazard gas station	Binary	False; true
Hazard wetlands	Binary	False; true
Hazard ocean	Binary	False; true
Hazard coffee	Binary	False; true
Hazard drycleaner	Binary	False; true
Hazard golf course	Binary	False; true
Hazard restaurant	Binary	False; true
Behavioral characteristics		
Number of pets	Continuous	0 to 7 or more
Meal prep weekly	Ordinal	9 or fewer meals per week, 10 or more meals per week, none of the above
Smoking in the house	Binary	False; true
Dependent variable		
Number of active health symptoms	Continuous	

Table A6

Summary statistics of variables from paid volunteers' survey

Variable	N	Mean	SD.	Min	Max
Demographics					
Building type					
Single family, detached	13,004	.72	.45	0	1
Multi-unit high-rise (<3 stories)	13,004	.19	.39	0	1
Multi-unit high-rise (>3stories)	13,004	.04	.21	0	1
Mobile/manufactured home	13,004	.04	.2	0	1
Range of year built	13,004	6.61	3.13	1	13
Square footage	12,789	3.41	1.4	1	8
Ownership					
Own	13,887	.68	.46	0	1
Rent	13,887	.31	.46	0	1
Military housing	13,887	0	.06	0	1
No. of people in household	14,195	6.65	1.86	4	40
Indoor characteristics					
Attached garage	16,286	.34	.47	0	1
Basement	16,286	.3	.46	0	1
Crawlspace	16,286	.18	.38	0	1
Fireplace	16,286	.38	.48	0	1
Heating system					
Forced/central	12,542	.64	.48	0	1
Baseboard	12,542	.07	.25	0	1
Radiant floor	12,542	.01	.1	0	1
Wall heater/furnace	12,542	.07	.26	0	1
Floor furnace	12,542	.02	.14	0	1
Wood stove/fireplace	12,542	.02	.14	0	1
Radiator	12,542	.04	.19	0	1
Heat pump	12,542	.07	.26	0	1
Not sure	12,542	.04	.2	0	1
No primary heating	12,542	.03	.16	0	1
Outdoor characteristics					
Hazard farm	16,286	.17	.37	0	1
Hazard airport	16,286	.03	.18	0	1
Hazard highway	16,286	.38	.49	0	1
Hazard industry	16,286	.04	.19	0	1
Hazard coffee	16,286	.05	.22	0	1
Hazard drycleaner	16,286	.08	.27	0	1
Hazard gas station	16,286	.18	.38	0	1
Hazard golf	16,286	.05	.21	0	1
Hazard restaurant	16,286	.2	.4	0	1
Behavioral characteristics					
Noticeable dust on sills	16,286	.09	.29	0	1
Maintenance frequency	13,004	2.38	.61	1	3
Noticeable odors	16,286	.12	.32	0	1
Noticeable surface dust	16,286	.26	.44	0	1
Noticeable water stains	16,286	.11	.31	0	1
Noticeable visible molds	16,286	.04	.2	0	1

No. of pests	16,286	.35	.67	0	5
No. of pets	14,195	2.64	1.64	1	7
Cook often (10 or more meals per week)	16,286	.27	.44	0	1
Smoking	16,286	.04	.2	0	1
Dependent variable					
Number of active health symptoms	16,286	1.20	2.90	0	22

N: Number of observation Min: Minimum Max: Maximum
SD: Standard deviation

Appendix B

Table B1

Demographic characteristics of the paid and volunteer participants

	Paid participants		Volunteer participants	
	Mean	SD	Mean	SD
Type of housing				
Single family, detached	0.72	0.45	0.63	0.48
Multi-unit high-rise (<3 stories)	0.19	0.39	0.20	0.40
Multi-unit high-rise (>3stories)	0.04	0.21	0.08	0.26
Mobile/manufactured home	0.04	0.20	0.10	0.29
Ownership				
Own	0.68	0.46	0.58	0.49
Rent	0.31	0.46	0.41	0.49
Military	0	0.06	0.02	0.13
Number of people in the household	6.65	1.86	2.84	1.60

Table B2

Summary of negative binomial regression analyses for indoor, outdoor, and behavioral characteristics on count of active health symptoms with volunteer participants

	Count of active health symptoms				
	(1)	(2)	(3)	(4)	(5)
Demographics					
Apartment[1]	-0.11***	-0.15***	-0.17***	-0.00	0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Range of year built	0.01***	-0.00	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Square footage	0.08***	0.09***	0.11***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Renter[2]	0.43***	0.39***	0.30***	0.12***	0.14***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Tenure	-0.00	-0.00*	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
No. of people in household	0.01***	0.02***	0.00	-0.01***	-0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Median annual income by zip code	-0.00***	-0.00***	-0.00***	-0.00***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Exterior of house in the sun		-0.24***	-0.23***	-0.02**	-0.02*
		(0.01)	(0.01)	(0.01)	(0.01)
Indoor characteristics					
Wood cladding[3]		-0.03***	-0.03***	-0.01	-0.00
		(0.01)	(0.01)	(0.01)	(0.01)
Garage		-0.11***	-0.11***	0.02**	-0.02*
		(0.01)	(0.01)	(0.01)	(0.01)
Basement		-0.06***	-0.06***	0.03***	0.01
		(0.01)	(0.01)	(0.01)	(0.01)
Crawlspace		0.05***	0.03***	0.02*	0.00
		(0.01)	(0.01)	(0.01)	(0.01)
Forced/central heating[4]		-0.05***	-0.04***	0.04***	0.03**
		(0.01)	(0.01)	(0.01)	(0.01)
Forced/central cooling[5]		-0.02*	0.01	0.02*	0.02
		(0.01)	(0.01)	(0.01)	(0.01)
Outdoor characteristics					
Proximity to farm			0.17***	0.10***	0.09***
			(0.01)	(0.01)	(0.01)
Proximity to airport			0.06***	0.07***	0.07***
			(0.02)	(0.02)	(0.02)
Proximity to highway			0.16***	0.10***	0.09***
			(0.01)	(0.01)	(0.01)
Proximity to industrial			0.18***	0.14***	0.13***
			(0.02)	(0.01)	(0.02)
Proximity to coffee			0.11***	0.11***	0.10***
			(0.03)	(0.02)	(0.02)
Proximity to drycleaner			-0.02	-0.01	0.00
			(0.03)	(0.03)	(0.03)
Proximity to gas station			0.05***	0.05***	0.04***

	Count of active health symptoms				
	(1)	(2)	(3)	(4)	(5)
			(0.02)	(0.01)	(0.01)
Proximity to golf course			0.01	0.06***	0.05**
			(0.02)	(0.02)	(0.02)
Proximity to restaurant			0.05***	0.03**	0.03**
			(0.02)	(0.01)	(0.02)
Noticeable dirt on sills			0.40***	0.18***	0.17***
			(0.01)	(0.01)	(0.01)
Maintenance behaviors					
Frequency of maintenance				-0.08***	-0.07***
				(0.01)	(0.01)
Counts of leak				0.11***	0.09***
				(0.01)	(0.01)
Noticeable odors				0.25***	0.24***
				(0.01)	(0.01)
Noticeable surface dust				0.29***	0.27***
				(0.01)	(0.01)
Noticeable water stains				0.08***	0.07***
				(0.01)	(0.01)
Noticeable mold				0.03***	0.02**
				(0.01)	(0.01)
Total number of pests				0.06***	0.05***
				(0.00)	(0.00)
Personal behaviors					0.03***
Total number of pets					
					(0.00)
Chemical storage indoor[6]					0.05***
					(0.00)
Scented personal or cleaning products					0.03***
					(0.01)
Windows are open					-0.05***
					(0.01)
Frequent long shower					0.05***
					(0.01)
Shoes are removed					-0.03***
					(0.01)
Smoking indoor					0.08***
					(0.01)
Frequency of meal preparation					0.02***
					(0.01)
Vacuum frequency					0.01***
					(0.00)
lnalpha	0.58***	0.55***	0.49***	-0.39***	-0.43***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Constant	1.31***	1.53***	1.22***	1.34***	1.03***
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)
Observations	60,650	59,807	56,820	38,249	35,046

	Count of active health symptoms				
	(1)	(2)	(3)	(4)	(5)
Deviance r-square	0.02	0.03	0.06	0.13	0.14

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Reference group for apartment is single-family home.
[2] Reference group for renter is owner.
[3] Reference group for wood cladding is brick, vinyl, stucco, concrete, cement, stone, and adobe cladding.
[4]Reference group for heating system is window air conditioner, evaporative cooler, whole house fan, window fan, and no heating system.
[5] Reference group for cooling system is baseboard, radiant floor, wood stove/fireplace, radiator, no cooling system, wall heater/furnace, and floor furnace
[6] Reference group for chemical storage indoor is chemical storage outdoor.

Table B3

Summary of negative binomial regression analyses for indoor, outdoor, and behavioral characteristics on count of active health symptoms with paid participants

	Count of active health symptoms				
	(1)	(2)	(3)	(4)	(5)
Demographics					
Apartment[1]	0.22***	0.21***	0.17**	0.08	0.05
	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)
Range of year built	0.04***	0.04***	0.03***	-0.02***	-0.02***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Square footage	-0.06***	-0.05***	-0.02	-0.02	-0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Renters[2]	0.47***	0.49***	0.37***	0.31***	0.29***
	(0.04)	(0.04)	(0.05)	(0.05)	(0.05)
No. of people in household	0.06***	0.07***	0.06***	0.04***	0.04***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Median income by zip code	-0.00***	-0.00***	-0.00***	-0.00*	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Indoor characteristics					
Garage		-0.03	-0.06	-0.12**	-0.10**
		(0.05)	(0.05)	(0.05)	(0.05)
Basement		-0.12**	-0.03	-0.01	-0.01
		(0.05)	(0.05)	(0.05)	(0.05)
Crawlspace		0.12**	0.08	0.07	0.07
		(0.05)	(0.05)	(0.06)	(0.06)
Forced/central heating[3]		-0.15***	-0.09**	-0.02	-0.02
		(0.04)	(0.04)	(0.05)	(0.05)
Outdoor characteristics					
Proximity to farm			0.23***	0.08	0.08
			(0.05)	(0.06)	(0.05)
Proximity to airport			0.21***	0.16*	0.16*
			(0.08)	(0.09)	(0.09)
Proximity to highway			0.27***	0.16***	0.16***
			(0.04)	(0.05)	(0.05)
Proximity to industrial			0.36***	0.25***	0.20**
			(0.07)	(0.08)	(0.08)
Proximity to coffee			-0.11	-0.02	-0.03
			(0.08)	(0.09)	(0.09)
Proximity to drycleaner			0.03	-0.01	0.00
			(0.07)	(0.07)	(0.07)
Proximity to gas station			0.36***	0.31***	0.28***
			(0.05)	(0.06)	(0.06)
Proximity to golf course			0.10	-0.05	-0.06
			(0.09)	(0.09)	(0.09)
Proximity to restaurant			-0.03	0.04	0.06
			(0.05)	(0.06)	(0.06)
Noticeable dirt on sills			0.89***	0.33***	0.32***
			(0.05)	(0.05)	(0.05)
Maintenance behaviors					

Frequency of maintenance				-0.21***	-0.18***
				(0.04)	(0.04)
Counts of leak				0.19***	0.19***
				(0.03)	(0.03)
Noticeable odors				0.56***	0.55***
				(0.05)	(0.05)
Noticeable surface dust				0.63***	0.61***
				(0.04)	(0.04)
Noticeable water stains				0.12**	0.12**
				(0.05)	(0.05)
Noticeable mold				0.25***	0.25***
				(0.07)	(0.07)
Total number of pests				0.20***	0.19***
				(0.03)	(0.03)
Personal behaviors					
Total number of pets					0.02
					(0.01)
Frequency of meal preparation					-0.10***
					(0.03)
Smoking indoor					0.51***
					(0.07)
lnalpha	1.60***	1.53***	1.43***	1.21***	1.19***
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Constant	0.21**	0.33***	-0.20*	0.03	0.11
	(0.10)	(0.11)	(0.12)	(0.16)	(0.18)
Observations	12,499	10,729	10,729	9,797	9,797
Deviance r-square	0.03	0.04	0.10	0.19	0.20

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Reference group for apartment is single-family home.
[2] Reference group for renter is owner.
[3] Reference group for heating system is window air conditioner, evaporative cooler, whole house fan, window fan, and no heating system.

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