An overview of indoor environmental conditions in work-from-home settings

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Abstract. During the last week of March 2020, about 4.7 million workers in Canada transitioned to working from home due to the pandemic. A similar transition occurred at a global scale. Few studies have evaluated the WFH setting from a perspective that's been a significant public concern during the COVID-19 pandemic: indoor environmental quality (IEQ). The objective of this paper is to present an analysis of the IEQ conditions in WFH settings based on a field study of 95 WFH sites during May-July 2022 in the Pacific Northwest region. The IEQ variables of air temperature, relative humidity, CO2, total volatile organic compounds, PM2.5, ambient light and noise were measured continuously at 10-minute intervals for the duration of the study. A preliminary analysis of the IEQ data shows the indoor air temperature in WFH settings within the study sample, ranged between 15.7-32°C, with a mean value of 22.7°C (*SD* = 2.3°C). The mean indoor concentrations of CO2, TVOCs and PM2.5 were 674 ppm (*SD* = 324 ppm), 288 ppb (*SD* = 515 ppb) and 4.7 μ/m^3 (*SD* = 20.5 μ/m^3) respectively. The mean values for relative humidity, light and noise were 53% (*SD* = 7%), 174 lux (*SD* = 349 lux) and 53 dB (*SD* = 5 dB). Associations between type of residence and most of the IEQ variables were found.

1 Introduction

Due to the COVID-19 pandemic, working from home has become the new normal. In 2008, 11.2% of Canadian employees worked from home, only 1% higher than in 2000. While there was an upward trend in the number of people working from home between 2000-2008, the increase was small [1]. Based on a survey of more than 4,600 people conducted between March 29 and April 3, 2020, 39.1% or 6.8 million Canadians worked from home during the last week of March, including those who usually work from home (before pandemic). So, about 4.7 million people transitioned to working from home during that week [2].

Several terms have been used to express the idea of working away from work/ office – telecommuting [3] telework, remote working, working from home (WFH), remote job, work from anywhere (WFA), mobile work, flexi-work, cyber commuting and home working. The idea of telecommuting is inextricably linked to the advent and development of information and communication technologies (ICTs) [4]–[7]. The earliest thought experiments and anecdotal discussions on the topic were published in the 1980s, marking the notion of balancing work and family life as its genesis. There were followed, invariably, by empirical studies.

Today, it is understood that four in ten (38.9\%) Canadian workers are in jobs that could be done from home [8]. And though many research studies have evaluated the WFH context since the 1980s, particularly from behavioral [9]–[11], psychological [12], [13], and sociological perspectives [14], [15] as only some examples, ironically few studies have evaluated the WFH setting from a perspective that's been a significant public concern during the COVID-19 pandemic: indoor environmental quality (IEQ).

To address this research gap, a doctoral project was initiated in March 2022 to undertake a systematic field study of WFH settings to evaluate the observed and perceived IEQ of WFH settings, as well as the perceived well-being and productivity of at-home workers. While the project is currently underway, this paper aims at presenting an exploratory analysis of the IEQ-based measurements undertaken during the field study. The methods pertinent to this paper are explained in the next section.

2 Methods

2.1 Study sites and participants

Ninety-five study participants (or WFH sites) were recruited through convenience and snowball sampling from Metro Vancouver region (*n* = 80) and Vancouver Island (*n* = 4) in Canada and Seattle Metropolitan area (*n* = 11) in the U.S. The inclusion criteria for participation in the study required that participants were healthy, employed adults working from home for at least two days a week, carrying out sedentary, computer-

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based work. The exclusion criteria were individuals with hearing or visual impairments, and those planning to move houses, carry out home renovations, or change their working location during the study period.

2.2 IEQ monitoring

After the recruitment was completed, each participant was given an indoor, desktop IEQ monitor with detailed installation instructions as well as protocols for the placement of these monitors in their WFH offices. The AWAIR Omni IEQ monitor measures indoor air temperature, relative humidity (RH), carbon dioxide (CO2), particulate matter 2.5 (PM2.5), total volatile organic compounds (TVOCs), light levels or illuminance (Lux), and noise and was identified as the best fit for this study. The technical specifications for the AWAIR Omni sensors are presented in Table 1. AWAIR Omni is a RESET [16] air accredited grade B monitor for indoor air quality, and also meets the requirements for WELL v2™ [17], Leadership in Energy and Environmental Design (LEED) v4 [18] and the Living Building Challenge (LBC) [19] certifications.

Once the IEQ monitors were distributed, each monitor was set up to connect to the participant's home WiFi network to allow continuous transmission of data to Awair's cloud-based servers. The sampling period for these IEQ monitors is 5 minutes. For the analysis presented in this paper all IEQ data were aggregated to hourly data and then median values of the entire monitoring period. The study/monitoring campaign ran for nearly nine weeks in summer of 2022. The analysis presented in this paper is based on the IEQ data collected from May 20 to July 20. Residences in the Pacific Northwest region tend to have operable windows and heating systems although a building-integrated cooling system is less common.

Table 1. AWAIR Omni technical specs

IEQ variable	Range	Accuracy	Output resolution
Temperature	-40 to 125°C	±0.2°C	0.015°C
Relative Humidity	0-100% RH	±2% RH	0.01% RH
Carbon Dioxide	400-5,000 ppm	±75 ppm or 10% of reading	1 ppm
Volatile Organic Compounds (VOCs)	0-60 ppm	±10%	1 ppb
Particulate Matter 2.5	0-1,000 μg/m³	±15% or ±15 μg/m³	1 μg/m3
Ambient light	0.96 to 64,000 Lux		
Ambient noise	Sensitivity: -26 dBFS	Signal to Noise Ratio: 61.5 dB(A)	

Hourly outdoor data for temperature and relative humidity were requisitioned from Environment Canada's Historical Climate Dataset for Vancouver and Vancouver Island [20] and from National Oceanic and Atmospheric Administration's (NOAA) Local Climatological Dataset for Seattle [21].

2.3 Participant questionnaires

A battery of survey instruments was used in this study for subjective assessment of comfort, well-being and productivity. The variables of interest being presented in this paper come from a one-time, bespoke background questionnaire that was deployed towards the start of the study campaign to gather information related to demographics, type and size of residence, living conditions, habits and workspace features.

Table 2. Independent variables and groups

Independent variable	Categories/ groups
Type of residence	An apartment / condominium / flat | A semi-detached house (i.e., townhouse, duplex, triplex, etc.) | A detached house
Size of residence by floor area	<500 sq ft. | 500-900 sq ft. | 900-1300 sq ft. | 1300-2000 sq ft. | 2000-3000 sq ft. | >3000 sq ft.
Size of residence by no. of bedrooms	Studio | 1 bedroom | 1 bedroom + den | 2 bedrooms | 2 bedrooms + den | 3 bedrooms | More than 3 bedrooms
Total number of residents	1 | 2 | 3 | 4 | 5 | 6
Frequency of cooking	Never | Less than once a week | Once or twice a week | 3-4 times a week | 5-6 times a week | At least once a day | At least twice a day
Most frequently used cooking method	Water-based cooking | Frying | Dry cooking
Type of workstation	It is a private office or a bedroom converted into an office (i.e., no-one sleeps there) | It is bedroom with an office workstation in it, and someone sleeps in the bedroom at night | It is a dedicated workstation located in a room that has other uses (i.e., hallway, living room, etc.) | It is a temporary workstation that I create at the dining table, in the living room, in other rooms, etc.

2.4 Statistical analysis

Statistical summaries (mean, standard deviation (SD), minimum, maximum and inter-quartile ranges) were used to describe the IEQ data. Statistical analysis was performed in Python using NumPy, Pandas, SciPy and scikit-learn packages. Normality of distribution was tested by D'Angelo K-Squared test. In order to compare IEQ data between different categories or groups of independent variables, Kruskal-Wallis test was used, followed by the Dunn's test for post-hoc multiple pairwise comparisons. *p*-values from the Dunn's test were adjusted using the Bonferroni adjustment to control the group-wise error rate. The categorical (or independent) variables used for the analysis are presented in Table 2.

3 Results

A statistical summary of the IEQ data is presented in Table 3. These statistics were calculated from the hourly aggregated mean values which, in turn, were calculated for the raw data measured on weekdays between 9am and 5pm. Most of the IEQ variables varied widely across the WFH spaces and/ or the monitoring period, as indicated by the minimum and maximum values. Temperature was found to be generally within the acceptable range of 19.4-27.8°C [22] except for the top 1.5 percentile which exceeded the higher limit and the bottom seven percentile which exceeded the lower limit. Relative humidity was also lower than ASHRAE'S maximum limit of 65%, except for the top six percentile of the data. However, if Canada's national guideline [23] is considered, nearly 39% of the samples exceed the 55% limit (for summer).

CO2 concentrations were generally lower than the Health Canada 24-hour average limit of 1000 ppm [24] with only top 13% percentile samples in exceedance. Standards or guidelines regarding the acceptable concentration of TVOCs vary a lot across the world which makes it difficult to assess this dataset. The study mean of 288 ppb exceeded the 200 ppb upper limit for level 3 (slightly increased – harmless) category by WHO [25] and even the less stringent target upper limit of 250 ppb based on 'acceptable' performance level from RESET [26], although at least 50% of the hourly samples were below these limits.

Table 3. Statistical summary of IEQ data

	Mean	SD	Q1	Q2	Q3	Min.	Max.
T (°C)	22.7	2.3	21.1	22.6	24.3	15.7	32
RH (%)	53	78	47	53	58	29	81
CO2 (ppm)	674	324	465	564	771	400	4864
TVOCs (ppb)	288	515	103	179	322	20	37906
PM2.5 (μ/m3)	4.7	20.5	1.1	2.0	3.1	0.0	747.1
Lux (lux)	174	349	22	66	176	0	9648
Noise (dbA)	53	5	50	52	56	40	80

PM2.5 concentrations were below the 24-hour average of 35 μg/m3 EPA limit [27] for nearly 98% of the samples. The Canadian Centre for Occupational Health and Safety (COHS) recommends minimum lux levels of 500 [28] for office-type work that involves using a computer. It seems that the lux levels in the study sample tend to ride lower than this minimum limit - less than 7% of the samples met this criterion. For noise or sound pressure level, the maximum allowable value prescribed by COHS is 85dbA [29] - the maximum value of the hourly samples was nearly within this limit. High variance (SD) and arithmetic means greater than medians for CO2, TVOCs and PM2.5 indicate the concentration data are log-normally distributed, which is typical of air pollutants in general [30].

More than 85% of the samples (*n* = 80)) came from WFH sites having the provision of an operable window. Nearly 32% samples (*n* = 30) were from sites that also had access to some form of mechanical cooling. For availability of fans, on the other hand, the samples were nearly split in half.

3.1 Residential attributes

The residential attributes of interest in this analysis are type of residence, floor area, number of bedrooms and number of household members. In this and the following sub-sections, the aggregate metric being used is the median value calculated for the entire monitoring period for each site and each IEQ variable. This means a sample size of ~95 points (corresponding to the 95 sites) for each IEQ variable.

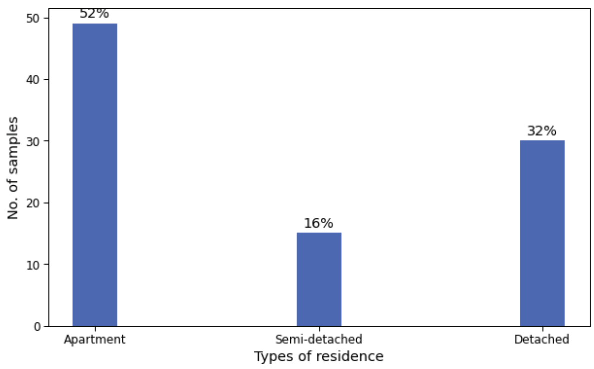

Fig. 1. Distribution of study samples by type of residence

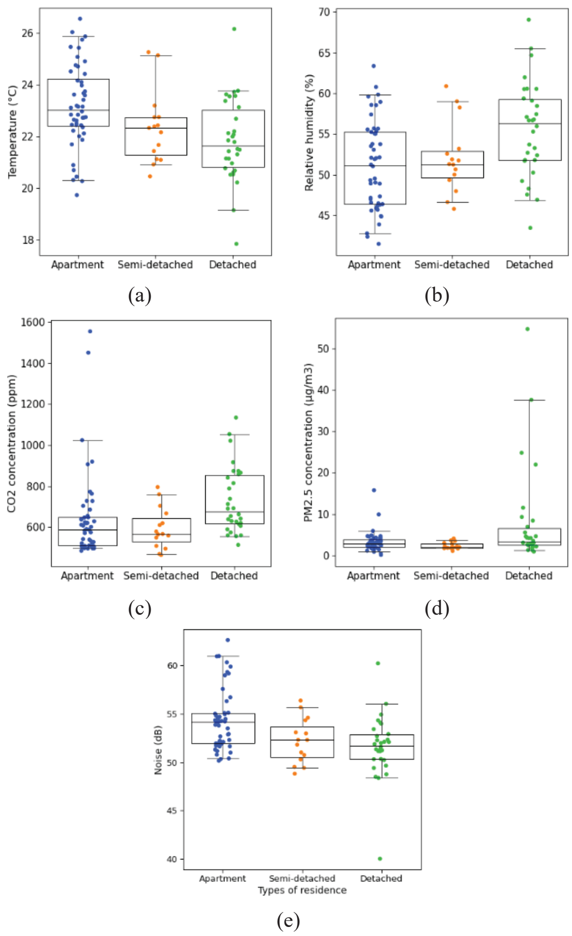

Fig. 2. Box plots by type of residence for (a) T, (b) RH, (c), CO2, (d), PM2.5, and (e) noise

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Fig. 3. Dunn's test outcomes for IEQ variables by type of residence (highlighted cells indicate significant p-values)

The distribution of samples across the three types of residences is shown in Fig. 1. Nearly half of the study samples were from WFH spaces in apartments (n = 48) while only 16% were from semi-detached houses (n = 15). The Kruskal-Wallis test outcomes showed that significant differences existed between the groups for five out of seven IEQ variables – T, RH, CO2, PM2.5 and noise. The box plots for these are shown in Fig. 2. We then used the Dunn's tests to find out which groups were significantly different from the others. The null hypothesis for the test is that there is no difference between the groups and $p > 0.05$ proves the null hypothesis. Fig. 3 shows a graphical matrix of the results where the highlighted cells show p-values < 0.05. There were significant differences between WFH spaces in apartments and detached houses for T, RH, CO2 and noise, and between semi-detached and detached houses for CO2 and PM2.5.

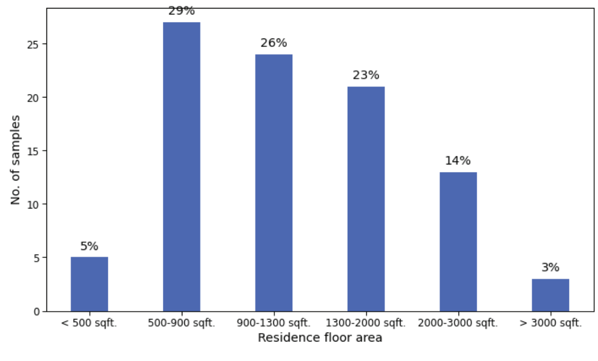


Fig. 4. Distribution of study samples by residence floor area

From the six floor area categories, the two extremes of <500sqft. and >3000sqft. had the least number of samples (n = 8). A majority of the samples, nearly 78% (n = 73), came from the three middle categories: 500-900sqft., 900-1300sq.t. and 1300-200sq.t (Fig. 4). Significant differences were found between these categories for T, RH and noise. The box plots (Fig. 5) show much variation in T and RH between the categories than in noise levels. For T, categories of 500-900sqft. and 900-1300sqft. were found to be different from 1300-2000sqft. and 2000-3000sqft. – these outcomes may also be influenced by the larger sample sizes in each of these categories (Fig. 6). For RH, 500-900sqft. was different from 2000-3000sqft. For noise, 500-900sqft. was different from both 1300-2000sqft. and 2000-3000sqft.

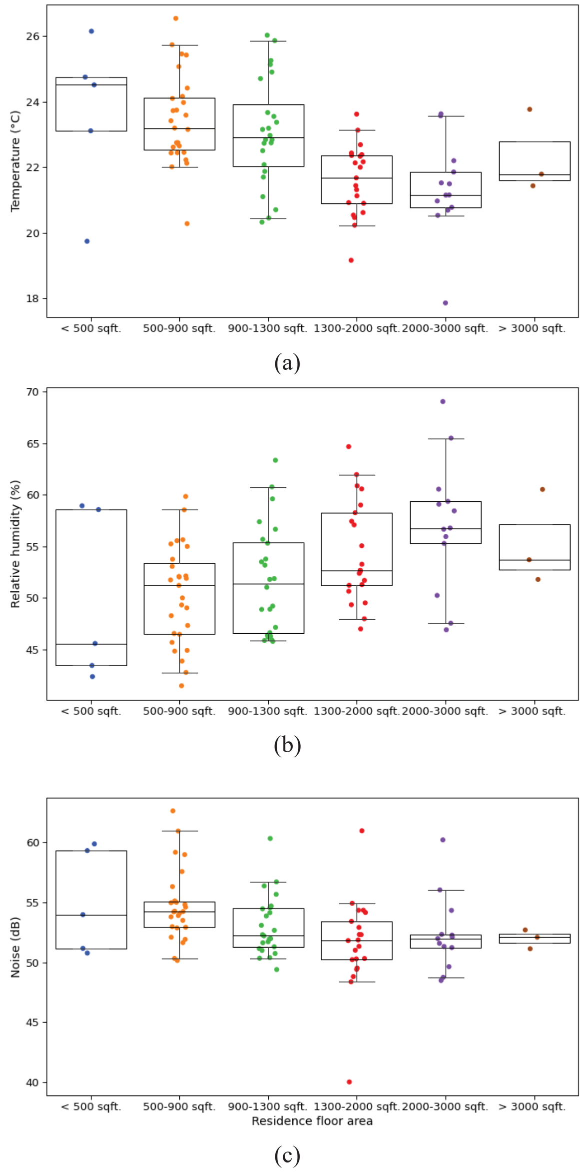


Fig. 5. Box plots by residence floor area for (a) T, (b) RH, and (c) noise

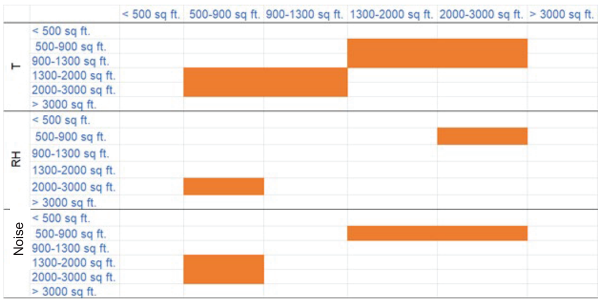


Fig. 6. Dunn's test outcomes for IEQ variables by residence floor area

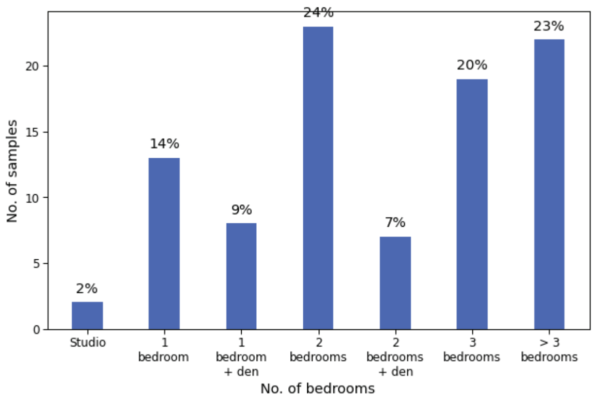
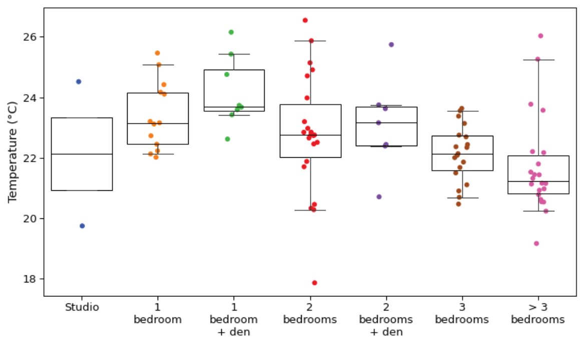
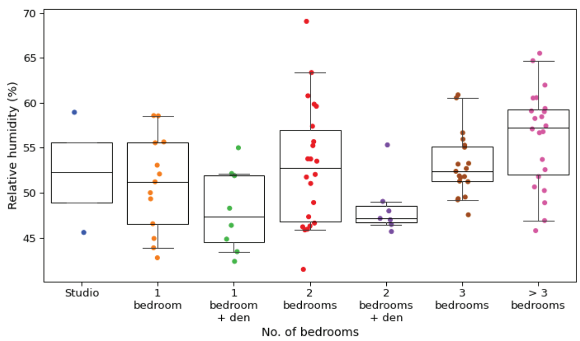


Fig. 7. Distribution of study samples by number of bedrooms



(a)



(b)

Fig. 8. Box plots by no. of bedrooms for (a) T, and (b) RH

Fig. 9. Dunn's test outcomes for IEQ variables by no. of bedrooms

Number of total household members was another variable of interest for this study, particularly for indoor pollutants like CO2, TVOCs and PM2.5, and for noise. Fig. 10 shows the distribution of samples across the six categories. Nearly 65% of the IEQ data samples came from households with 2 or 4 members (including children) (n = 61). Large households of more than 4 people were under-represented (n = 4). We did not find any differences between the categories for any of the IEQ variables.

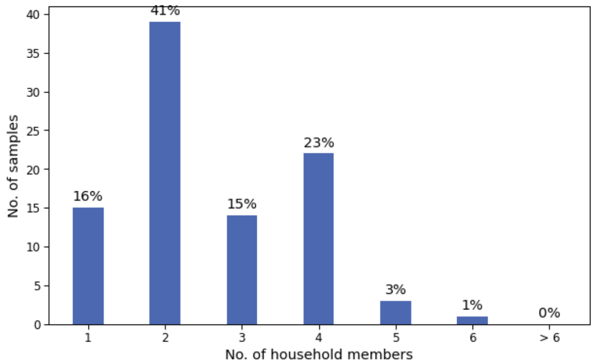


Fig. 10. Distribution of study samples by number of household members

3.2 Cooking habits

Cooking habits, by way of fuel types being used or the kind of cooking being done, have been known to influence concentrations of both PM2.5 [31] and TVOCs [32], [33]. So, for this study, two questions pertaining to cooking habits were included in the questionnaires. The distribution of samples by frequency of cooking is shown in Fig. 11. The “never” category had no samples. More than 80% of the samples came from households where occupants engaged in cooking for “3-4”, “5-6 times a week”, or “at least once a day” – the latter category had the highest number of samples (n = 31). Surprisingly, we did not find any differences between the categories for PM2.5 concentrations, but we did find differences for T, TVOCs and noise. For T, the differences were significant between “3-4 times a week” and “5-6 times a week” categories. For TVOCs and noise, “once or twice a week” and “at least twice a day” categories were different (Fig. 12).

The second variable related to cooking habits was about the kind of cooking methods used by the participants. Fig. 14 shows that the samples were equally distributed between the three categories for the most frequently used cooking methods. Although cooking methods seemed like an important variable to consider for TVOC concentrations, we did not find any significant differences between the three types of cooking methods for TVOCs or any other IEQ variables.

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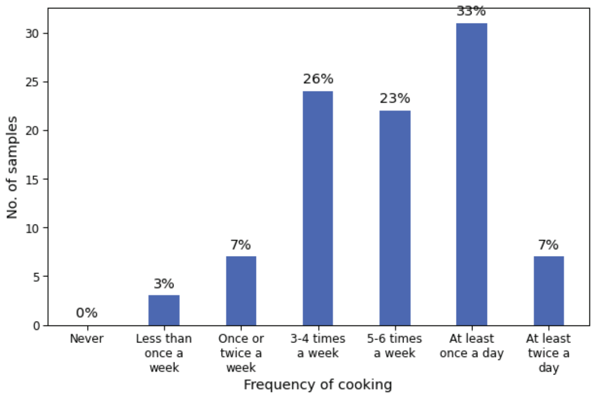
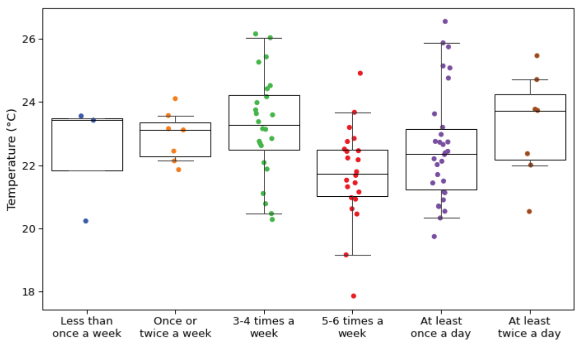
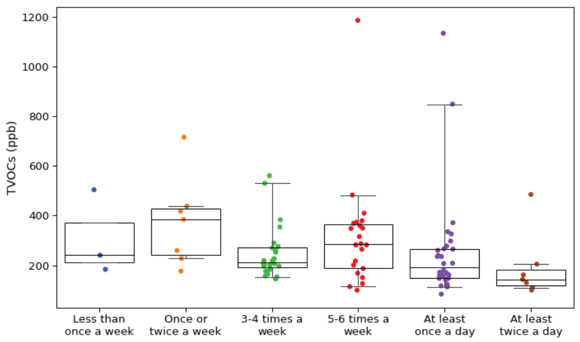


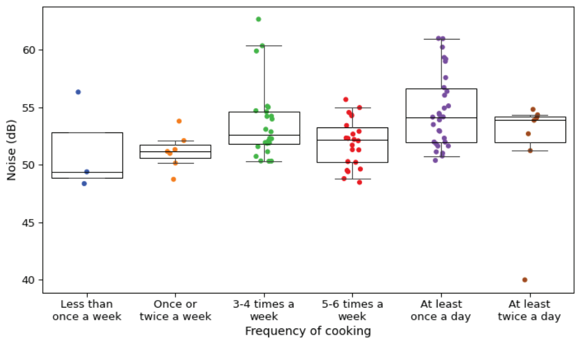
Fig. 11. Distribution of study samples by frequency of cooking



(a)



(b)



(c)

Fig. 12. Box plots by frequency of cooking for (a) T, (b) TVOCs, and (c) Noise

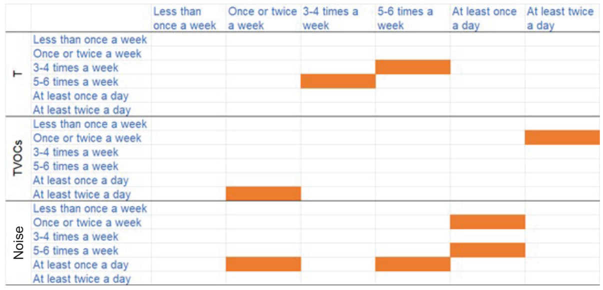


Fig. 13. Dunn's test outcomes for IEQ variables by frequency of cooking

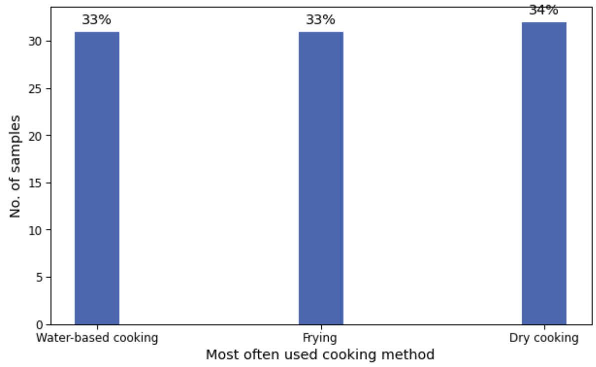


Fig. 14. Distribution of study samples by the most often used cooking methods

3.3 Workspace typology

The four categories for type of workspace offer a combination of variables that are relevant for workspaces, although they are not extensive definitions. The most important aspect of workspace they include is privacy and flexibility, where the "it is a private office…" may be considered to offer the highest and the "it is a temporary workstation…" the lowest level of privacy and flexibility for a WFH workspace. This range also indicates, to some measure, the interaction between workspace environment and that of the rest of the residence. A private office that is physically separated may have IEQ conditions that are different from other spaces. A private office type of workspace was also from where 45% (n = 42) of study samples came, followed by "it is a dedicated workstation…" (n = 22) (Fig. 15). Only 10% of the study population worked at a temporary workstation (n = 9). While we considered this to be an important independent variable, we did not see any differences between the workspace types for any of the IEQ variables.

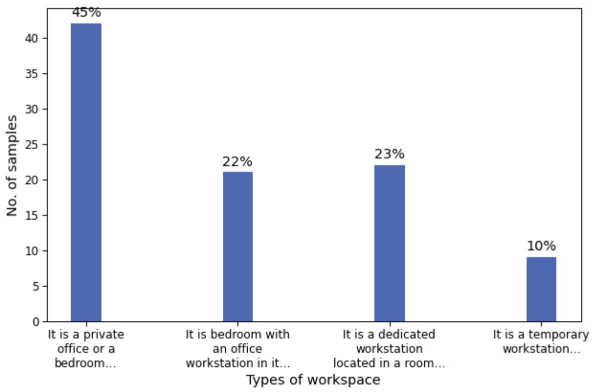


Fig. 15. Distribution of study samples by type of workspace

4 Discussion

All residential attributes discussed in this paper may be considered a combination of multiple proxy variables that are pertinent to IEQ conditions – ventilation and daylight opportunities, envelope characteries, air tightness, etc. It is, therefore, not surprising that significant differences were found between types of residence for most of the IEQ variables. The outcomes of the Dunn's showed significant differences between apartments and detached houses. We have used *p*-values to make this determination which are dependent on the mean differences in ranks. However, it is important to note that they are also affected by the sample size in each group. So, it is possible that to get less significant p-values for groups with less samples even though the sample mean rank difference may be the same. A case in point is the group-wise comparison for RH in Fig. 2 (b). Even though the median values of the apartments and semi-detached house are nearly same, the p-value for apartment-detached houses is significant while for semi-detached-detached houses is not significant, likely because of the relatively small sample size for semi-detached houses.

Our analysis of cooking habits did not reveal any significant association with PM2.5 although differences in WFH space TVOC concentrations were found between households where cooking was done more often and less often. It is important to note here that measurements for nearly all the air quality related variables, particularly TVOCs, need to be validated against reference instruments before we perform a more detailed analysis on these data.

We also did not find associations between workspace type and IEQ conditions. Other questionnaires deployed in the study provide us with the opportunity to delve deeper into this relationship through questions regarding the features available at these workspaces. The work presented in this paper needs to be reinforced and augmented by more analysis.

5 Conclusion

This study presented the preliminary outcomes of a monitoring-based field study of IEQ conditions in work-from-home settings. An analysis of the IEQ data gathered from 95 sites in the Pacific Northwest region for two months in summer shows the indoor air temperature in WFH settings within the study sample ranged between 15.2-31.1°C, with a mean value of 22.5°C (SD= 2.2°C). The mean indoor concentrations of CO2, TVOCs and PM2.5 were 653.1 ppm (SD=252.4 ppm), 268.2 ppb (SD=413.0 ppb) and 4.9 μ/m^3 (16.7 μ/m^3) respectively. The mean values for relative humidity, light and noise were 52.8% (SD=7.5%), 165.1 lux (SD=291.2 lux) and 53.1 dB (SD=4.1dB).

Associations between type of residence and IEQ variables of temperature, relative humidity, CO2, PM2.5, noise; between residence floor area and temperature, relative humidity, noise; between number of bedrooms and temperature, relative humidity; and between frequency of cooking and temperature, total volatile organic compounds, noise were found.

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