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Perceived air quality and satisfaction during implementation of an automated indoor air quality monitoring and control system

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ABSTRACT

Cooking and cleaning are among the largest sources of home pollutant emissions. To reduce these emissions, we developed an automated indoor air quality (IAQ) control intervention that operated based on real-time sensor readings of particulate matter ($PM_{2.5}$) and evaluated the perceptual differences between this intervention and a baseline condition. We employed a 14-participant crossover study design in a one-bedroom apartment module. Participants experienced one of two conditions: (1) Advanced Control–automated IAQ interventions including a stove hood, two portable air cleaners, and a bathroom exhaust powered on/off based on predefined $PM_{2.5}$ thresholds measured by environmental sensors; and (2) Standard Control–participants controlling IAQ interventions (*e.g.*, stove hood) manually. Each condition lasted two weeks. Participants followed standardized cooking and cleaning protocols and filled out surveys assessing psychosocial and perceptual outcomes. Observations indicated that weekly IAQ satisfaction, perception, and preferences were similar between the two conditions—despite lower $PM_{2.5}$ concentrations during cooking and cleaning for the Advanced Control versus Standard Control Condition. When pairing IAQ complaints with $PM_{2.5}$ concentrations during cooking, we observed participants made complaints when $PM_{2.5}$ concentrations $>\sim 80$ μg/m^3 but few complaints when $<\sim 60$ μg/m^3. Lower $PM_{2.5}$ concentrations were observed for the Advanced Control versus Standard Control Condition during cleaning, but these lower concentrations did not appear perceivable by participants due to far lower $PM_{2.5}$ concentrations during cleaning overall. Our observations suggest a connection between $PM_{2.5}$ concentration and IAQ complaints made by participants, thereby providing possible thresholds for perceivable IAQ changes.

1. Introduction

Most individuals spend more than 90% of their day indoors [1]. As such, indoor environmental quality (IEQ) can significantly affect human health and productivity [2]. In residential settings, indoor air quality (IAQ) is an IEQ component that can have notable health impacts. Common household activities, such as cooking, can emit different types of indoor air pollutants including particulate matter $(PM)_{2.5}$, PM_{10} [3,4], and, secondary particles like volatile organic compound (VOC), sVOC, etc. [5,6]. Household cleaning products also emit VOCs [7,8]. The increased levels of particulate air pollutants have detrimental impacts on cardiorespiratory [9,10] and psychosocial/perceptual health [11,12].

Multiple IAQ interventions have been studied to reduce pollutant levels associated with household activities in residential environments, including stove hoods [13], portable air cleaners [14], and natural ventilation [15]. Among household activities, indoor cooking often emits among the largest amounts of indoor air pollutants [16]. Mechanical ventilation by design first mixes cooking emissions in the whole volume of the space to dilute air pollution. Natural ventilation also relies on mixing and dilution to remove pollutants. During this process, cooking emissions would expose occupants present in the space and therefore these systems are not considered as effective methods for cooking emission control. Instead, stove hoods are considered as most effective method for cooking emission control given that they are closest to the pollutant source [17]. However, air pollutant capture efficiency has varied considerably in these studies owing to differential stove hood air flow rates, the location of the stove's burner in relation to the stove hood [13,17–19], and patterns of stove hood use [20]. Using multiple IAQ interventions, such as a stove hood or portable air cleaner(s)

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combined with natural ventilation, has been shown to enhance the ability to effectively improve the capture and removal of cooking related emissions compared to ventilation alone [21].

The development of real-time IAQ monitoring systems utilizing Internet of Things (IoT) sensor technology has led to advancements in measuring and deploying interventions to improve IAQ [22], with the ability to control IAQ interventions based on real-time sensor readings. Due to their complexity, automated systems that monitor IAQ and actuate one or more IAQ interventions are rare to find within the literature. As one example, we showed that automating a stove hood, portable air cleaners, and the bathroom exhaust of a small apartment to power on at specific $PM_{2.5}$ thresholds was particularly impactful at efficiently reducing cooking generated $PM_{2.5}$ concentrations, adding further evidence to the IAQ benefits of real-time IoT sensing and, more generally, automated IAQ control systems [23–25].

Despite realizing the measurable IAQ benefits through automated IAQ control systems, only one study investigates the impact of automated system of IAQ interventions and a few studies investigated the impact of automated portable air cleaners on different pollutant sources in the residential environment. None assessed the subsequent impact on occupant satisfaction, perception, and comfort, among other health outcomes. Indeed, the connection between PM concentrations and perceived air quality (PAQ) in the residential environment has typically been examined without any specificity as to home activities [26,27]. Among the limited number of studies about home PAQ, the impact of smoking behavior has been the most frequently examined given its impact on PM concentrations [28,29]. Yet, studies assessing PAQ in relation to an automated IAQ intervention to manage cooking and cleaning emissions are crucial given that these activities are completed most frequently within residences and thus provide the greatest chance to impact health or the residents [30]. Observations could assist in finding a balance between the design and implementation of automated IAQ control interventions and health improvements [31].

In a cross-over multi-month study, we examined the impact of Advanced and Standard air quality Control conditions (details in the methodology section) on multiple physiological and psychosocial human health outcomes in a residential environment. The details about the study's methodology can be found in a prior publication [32]. Overall project findings indicate that Advanced Control (automation of stove hood, tow PACs, and bathroom exhaust) can reduce the indoor concentration of cooking emitted particles up to ~90% compared to air supply alone, but when participants were able to turn on the stove hood manually reduction of the indoor concentration of cooking emitted particles was ~40%. Herein, we present results regarding the perceptual differences observed between an Advanced Control Condition (*i.e.*, automated IAQ control) and a Standard Control Condition (*i.e.*, standard IAQ control typical of most residences). We hypothesized that: 1) improved IAQ perceptions, overall and during episodic particle emission events such as cooking and cleaning, and lower $PM_{2.5}$ concentrations would be observed during the Advanced Control versus Standard Control Condition; and 2) regardless of the condition, IAQ perceptions would differ by: (a) $PM_{2.5}$ concentration levels; and (b) activity type (*i.e.*, cooking versus cleaning).

2. Methodology

2.1. Experimental environment

Experiments were conducted in two residential modules in the Well Living Lab (WLL; Rochester, MN, USA). The two residential modules had identical floor plans, with a layout composed of a living room, bedroom, kitchen, and bathroom and so mimicked a real-world residential apartment. Both modules had a floor area of 32.6 m^2, with 2.6m-high ceilings. The kitchen was fully equipped for cooking tasks including electric cooktop, stove hood exhaust, fridge, and dishwasher. Windows in the modules were unopenable. Photos of the residential module are presented in Fig. 1.

2.2. Study design, experimental conditions, and participants

A crossover study design was employed, with participants experiencing two Conditions:

Advanced Control Condition - Automated IAQ interventions including a stove hood in the kitchen (Panasonic WhisperHood IAQ™; Osaka, Japan), two portable air cleaners in the living room and bedroom (Blueair 480i; Stockholm, Sweden), and a bathroom exhaust (Panasonic FV-0511VK2; Osaka, Japan). Each room had IoT PM sensors (PurpleAir PA-II; Draper, Utah, USA) that algorithmically controlled these IAQ interventions according to the specifications outlined in Table 1, with a pictorial representation in Fig. 2. Briefly, when a $PM_{2.5}$ reading from a collocated IoT PM sensor detected an indoor concentration >15 μg/m^3, the collocated IAQ intervention(s) would be powered on, with the stove hood operated at a flow rate of 577.8 m^3/h, the portable air cleaners operated at a flow rate of 595 m^3/h (clean air delivery rate of approximately 510 m^3/h), and the bathroom exhaust operated at an air flow rate of 109 m^3/h. These IAQ interventions were powered off when three consecutive $PM_{2.5}$ readings from a collocated IoT PM sensor were <6 μg/m^3. The participants were not allowed to override any controls. The centralized heating, ventilation, and air-conditioning (HVAC) system supplied 204 m^3/h of air, required by ASHRAE 62.2. Depending on the outdoor climate, heating and cooling were active at various proportions across participants, and participants were provided the ability to adjust air temperature between 21 and 25 °C, as desired.

Standard Control Condition – Manual control of IAQ interventions including bathroom exhaust at an air flow rate of 109 m^3/h and the stove hood at three fan speed levels with flowrates ranging from 221 to 577.8 m^3/h. Portable air cleaners were present but not active during the Standard Control Condition. Required ventilation by ASHRAE 62.2 was provided by centralized HVAC system and participants adjusted air temperature, as desired.

Details of the environmental control for each residential module are provided in the subsequent sections. Participants were provided written instructions and engaged in an onboarding session prior to moving into the residential modules. During the onboarding session, participants were instructed how to operate the stove hood in addition to being told that they were not to manually operate the portable air cleaners but that they may hear these portable air cleaners running automatically at certain points during the study. Participants spent ten weekdays in each condition (a total of 20 weekdays or 4 total weeks) but were randomly assigned to the sequence in which they experienced each condition (Advanced Control Condition then Standard Control Condition, or vice versa). Participants followed the same daily schedule throughout the study. However, the schedule's start and stop times were tailored slightly for each participant given their varying work schedules. Generally, the schedule included the periodic completion of surveys and various physiological measurements, the daily cooking of breakfast and dinner using standardized recipes and cooking techniques on an electric cooktop, and the twice-weekly cleaning of their residential module using a standardized cleaning protocol. Importantly, participants were requested to stay in their residential module at least 1.5 h around cooking events to ensure accurate health measurements related to their $PM_{2.5}$ exposure.

The study cohort consisted of fourteen participants (7 females, 6 males, 1 other) with mean age: 47 ± 11.5 years. Inclusion criteria were: (1) 18+ years old; (2) Mayo Clinic employees, contractors, affiliates, or volunteers; (3) non-shift workers; (4) willingness to reside in WLL residential modules for four weeks, excluding weekends; (5) fully vaccinated for COVID-19; and (6) willingness to complete all study tasks and provide informed consent. Exclusion criteria were: (1) current smokers or having quit smoking <1 year before study participation; (2) individuals with a current respiratory infection; (3) those with signs and symptoms of obstructive pulmonary disease, asthma, heart failure, or a

Fig. 1. Photos of the residential module.

Table 1
IoT $PM_{2.5}$ sensors triggered controls.

IoT $PM_{2.5}$ sensor location	Activated control	Threshold to trigger	Threshold to stop
Bedroom	Portable air cleaner	15 μg/m^3	6 μg/m^3
Living room	Portable air cleaner	15 μg/m^3	6 μg/m^3
Kitchen	Stove hood	15 μg/m^3	6 μg/m^3
Bathroom	Bathroom exhaust	15 μg/m^3	6 μg/m^3

cardiac arrhythmia; (4) persons using corticosteroids, antiarrhythmics, beta-blockers, anti-inflammatory drugs, or aspirin; (5) women who were pregnant or intended to become pregnant during the study; and (6) shift workers. Additional exclusion criteria included individuals who tested positive for COVID-19 during enrollment. The Mayo Clinic Institutional Review Board (IRB) approved all study procedures (Mayo Clinic IRB #: 20–007908). All participants provided written informed consent before the initiation of any study procedures.

2.3. Survey deployment and selected questions

Six surveys were deployed throughout the study via Qualtrics (Provo, UT; Appendix A) using an iPad. Three surveys represented one-time deployment surveys while three surveys were conducted at a frequency greater than or equal to weekly. Our analyses focus on IEQ questions regarding the satisfaction, perception, and preferences for different environments' thermal, air, lighting, and acoustic conditions. Briefly, we gathered data from one-time surveys regarding these IEQ related satisfaction, perception, and preferences for participants' real-world residences and workplaces. The one-time surveys were collected before the participants move in to the residential modules. From weekly surveys, we gathered information on these IEQ satisfaction, perception, and preferences when living in the residential modules at the end of each study week while also gathering IAQ specific responses around cooking (twice daily-right after cooking breakfast and dinner) and cleaning events (twice weekly right after cleaning events). Fig. 3 describes the overall timeline for each survey.

The same questions were included for satisfaction, perception, and preferences across all IEQ components. Chief among these questions

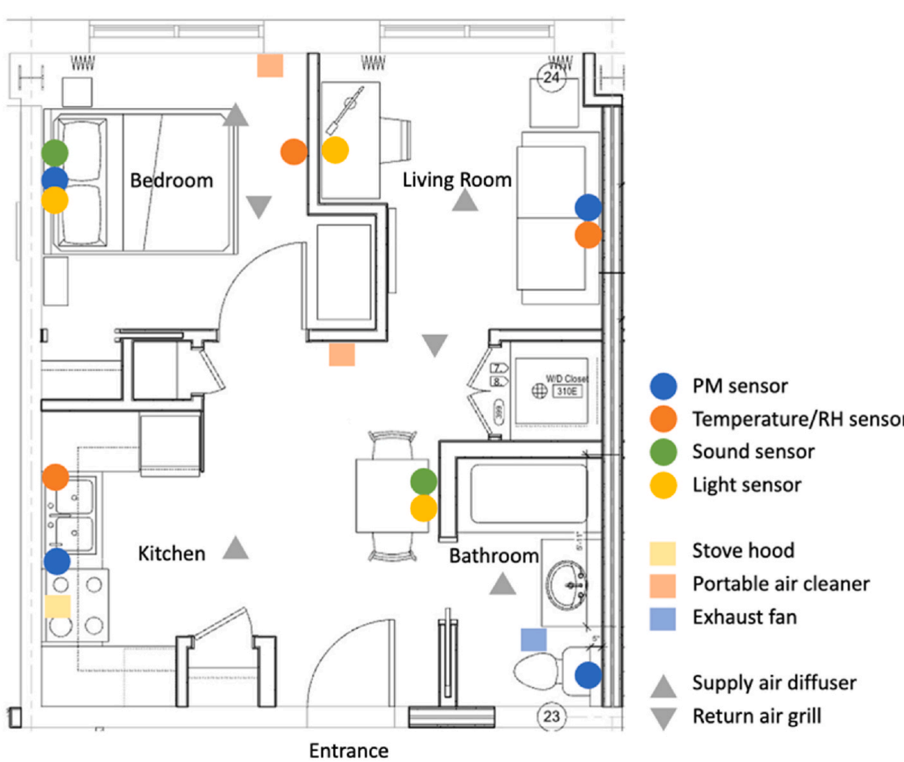

Fig. 2. Sensor placement and intervention locations on floor plan.

were queries regarding IAQ: 1) *satisfaction* – assessed using a 7-point Likert scale from 'Very dissatisfied (1)' to 'Very satisfied (7)'; 2) *perceptions* – assessed using a 7-point Likert scale from 'Very bad (1)' to 'Very good (7)'; and 3) *preferences* – assessed using a 3-point scale of 'Much better air quality (1)', 'Better air quality (2)', and 'No change (3)'. Notably, some questions asked more specifically about IAQ during cooking or cleaning and included outcomes such as: 1) *odor intensity* – assessed during cooking and cleaning using a 6-point Likert scale from 'No odor' to 'Overwhelming odor'; and 2) *IAQ complaints*– collected during cooking only for the following IAQ complaints: 'stuffy,' 'odor,' 'dusty,' 'smoky,' and 'other'.

2.4. Indoor environmental quality measurements

We employed multiple sensors to measure all aspects of the residential module environment. The number and location of sensors were carefully determined to capture the variability of environmental parameters in the module. We explored the impact of sensor location on measurement of $PM_{2.5}$ dispersion pattern and Advanced Control investigated in this study. We placed multiple sensors in each space to observe the speed of detection and concentration level measured. Results suggested that sensor location in the kitchen is critical for the timely detection of cooking emissions, and we placed the sensor on the stove hood. $PM_{2.5}$ concentration differed across spaces, indicating that for accurate detection of concentration levels, measuring $PM_{2.5}$ concentration in each space was critical, but the exact location was less critical. Description of investigated variability in sensor location is described in our previous publication [25] and the lessons learned were applied in this experimental setup. We measured $PM_{2.5}$ concentrations every 2 min using PurpleAir PA-II sensors at the locations shown in Fig. 2. The PurpleAir PA-II sensors measured particles in six size bins: 0.3, 0.5, 1, 2.5, 5, and 10 μm, with a measurement range of 0–1000 μg/m^3. Measurement errors for the PurpleAir PA-II were ±10 μg/m^3 for measurements under 100 μg/m^3 and ±10% for measurements between 100 and 500 μg/m^3. Cumulative $PM_{2.5}$ concentrations were measured from 0.1L of sampled air. All $PM_{2.5}$ sensors were calibrated within a recirculating wind tunnel at the University of Minnesota following the study [33], with correction factors for each sensor from this post-study calibration applied to the raw data collected during the study. Importantly, during these calibration trials, a Blaustein Atomizing Module (BLAM) generated particles from a 3–5 wt% solution for 25, 60, 110, 180 μg/m^3 of nominal mass concentration to represent the range observed during the study, with the aforementioned correction factors derived from a curve-fitted slope with a zero intercept.

Temperature (°C), relative humidity (RH, %), CO_2 (ppm), and Total Volatile Organic Compounds (TVOC) were measured every minute in the kitchen, bedroom, and living room using a Sensedge Mini (Kaiterra, Valais, Switzerland) with measurement range and errors of –20-100 °C, ±1 °C; 0–99%, ±5% RH; 400–2000 ppm, ±50 ppm; 0–60000 ppb, ±15% ± 8 ppb, respectively.

Noise levels (dBA) were collected every 30 s using NSRTW_Mk2 acoustic sensors (Convergence Instruments, Quebec, Canada) in the kitchen and bedroom. Finally, light levels (illuminance, lx) were measured every 5 min using Wovyn light sensors (ColorLux1000, Salt Lake City, UT, USA) in the kitchen, living room, and bedroom. The locations of these latter three sensors are also marked in Fig. 2.

2.5. Data collection and analyses

Data were collected real-time from the IoT sensors listed in section 2.4, streamed to our Microsoft Azure, IoT hub, and stored in our Microsoft SQL database. Following collection and storage in Qualtrics, survey responses were migrated to our Microsoft SQL database. The analysis and visualization took place in RStudio 4.2.1 through direct connection to the SQL database using DBI, obcd, ggplot2, lubridate, tidyverse, plyr, and reshape2 packages. We first examined all data for completeness. Next, we cleaned all environmental and response data, thereby removing duplicated instances, filtering data for the actual experimental dates, excluding two participants who dropped out in the middle of the study and who missed most cooking activities, and removing outliers from the $PM_{2.5}$ data. We then performed descriptive analyses to characterize our data. Finally, a series of statistical analyses were conducted including Shapiro-Wilk tests to check data normality, Wilcoxon or t-tests to compare responses and $PM_{2.5}$ concentration between the two Conditions, ANOVA to compare responses in different environments (*i.e.*, between participants' real-world residences [home] and work [office] as well as the residential module), Fisher's exact tests to compare the number of complaints during cooking between the two Conditions, and Pearson correlations to examine the relationship between general IAQ and activity-specific IAQ responses.

3. Results & discussion

3.1. Survey response rate and data completeness

Response rates for the three one-time surveys – the baseline, home environment, and office environment surveys – were 93% (13/14), 100% (14/14), 100% (14/14), respectively. Response rates for the three repeated surveys – the end of week, cleaning, and cooking surveys – were 93% (52/56), 96% (108/112), 88% (492/560), respectively. Regarding environmental data, the overall completeness of $PM_{2.5}$ concentration data was 95.92%, and the daily completeness was higher than 80%. The RESET Standard suggests ≥80% data completeness as a data collection quality benchmark [34].

Environmental sensing data, including $PM_{2.5}$ concentrations, was collected in real-time, streamed to the Microsoft Azure IoT hub, and stored in the Microsoft SQL database. Since cooking-generated $PM_{2.5}$ was the major pollutant in this study, we evaluated data completeness for $PM_{2.5}$ concentrations and associated cooking activities. The data completeness for $PM_{2.5}$ concentration data was higher than 80% for all participants across all but five days of the 314-day study period (I.e., 20 days each for 14 participants, with six days excluded initially due to one participant's schedule). Notably, even during the five days during which data completeness was <80%, data completeness was still between 60 and 80% despite a network outage and other unknown issues impacting data acquisition.

The exact start and stop times for cooking were determined primarily by data from a circuit monitor connected to the stovetop (Sense Labs Inc., Cambridge, Massachusetts). Briefly, the circuit monitor allowed us to determine when the stove was turned on and off which largely, but not always, correlated with the beginning and end of the cooking session. Given that individuals may have started the stovetop prior to cooking and/or left the stovetop on for a few minutes after cooking, we

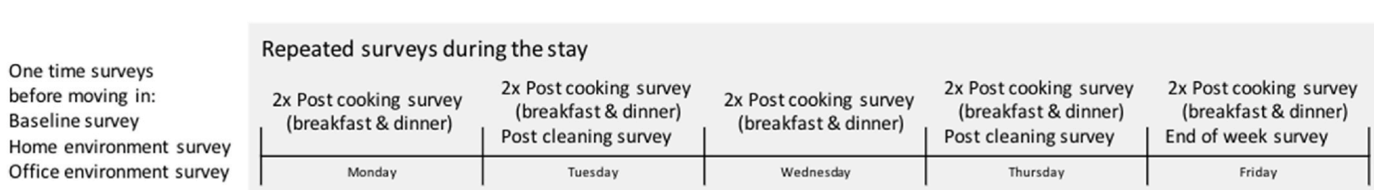

Fig. 3. Survey timeline diagram.

also examined $PM_{2.5}$ concentration data from the sensor mounted on the stove hood to further refine the accuracy of our cooking start and stop times. Specifically, we examined the actual $PM_{2.5}$ concentrations for all cooking events to see if they were elevated compared to the average background levels measured outside the cooking period.

3.2. IAQ satisfaction, PAQ, and IAQ preferences

Participants rated IAQ satisfaction between 'Slightly satisfied' and 'Satisfied' and PAQ between 'Slightly good' and 'Good' across both conditions, with most participants desiring no change to the IAQ within the module during either condition (Fig. 4). Further, participants had mean overall satisfaction scores between 'Slightly satisfied' and 'Satisfied' for the overall residential module environment regardless of the condition (Table 2). As satisfaction with the thermal and visual environments most greatly affects overall satisfaction [35], high overall satisfaction in this study confirmed that the residential modules offered satisfactory visual and thermal environments via the controllability of the thermostat, lighting, and window shades. Thus, it is unlikely that these IEQ components confounded our IAQ perception results.

Results indicated IAQ satisfaction was slightly higher in the Standard Control Condition relative to the Advanced Control Condition (Fig. 4a and Table 2). Notably, the Advanced Control Condition did not enable any manual override of the IAQ intervention, with all interventions operated based on an automation scheme related to $PM_{2.5}$ levels. Yet, the Standard Control Condition enabled participants to manually control stove hood and bathroom exhaust operation. Past research [36–40] showed that enabling occupants to control indoor thermal and visual conditions had a positive impact on satisfaction. When extrapolated to IAQ satisfaction, the ability to have personalized control over the IAQ interventions in comparison to fully automated IAQ interventions may explain our observations.

No significant differences were observed for overall and IAQ satisfaction, or for PAQ and IAQ preferences, between participants' real-world home and office environments and the residential module environment set up in either condition. Similar environmental perceptions between real-world home and residential module environments validated the experimental design where we tried to simulate home environments in the residential modules. Interestingly, although participants reported better IAQ satisfaction and PAQ within their real-world work environment, they still stated a greater preference for better IAQ in this setting relative to their real-world home environment or the residential module environment set up in either condition. While it is difficult to surmise the exact reason behind this observation, it is worth noting that this study occurred during the COVID-19 pandemic. Thus, concerns about disease transmission and heightened attention on IAQ might be a plausible explanation for the greater preference for better IAQ in the work environment versus. the other environments.

Table 2
Average IAQ satisfaction, perception, and preferences with IAQ in home, office, and residential module.

	Home	Office	Residential module Standard condition	Residential module Advanced condition
Overall satisfaction[a]	5.20	6.00	5.56	5.48
IAQ satisfaction[a]	5.00	5.75	5.44	5.33
PAQ[b]	5.40	5.75	5.20	5.19
IAQ preference[c]	2.20	2.00	2.48	2.52

[a] 7-point Likert scale from Very dissatisfied (1) to Very satisfied (7) to.
[b] 7-point Likert scale from Very bad (1) Very good (7).
[c] 3 response options: Much Better Air Quality (1), Better Air Quality (2), and No Change (3).

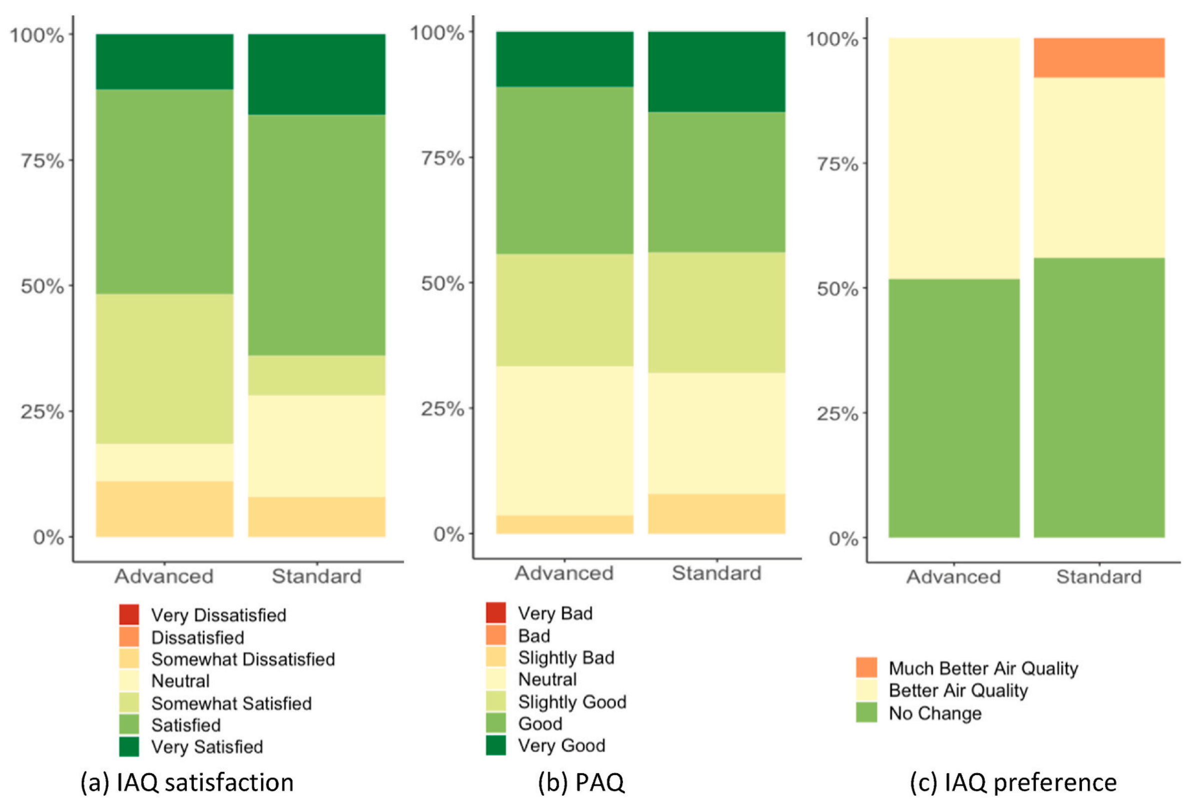

Fig. 4. IAQ related subjective responses in advanced control condition and standard control condition.

3.3. Subjective responses regarding IAQ in relation to PM concentrations while cooking

$PM_{2.5}$ concentrations measured in the residential modules during cooking were marginally lower in the Advanced Control Condition (85 μg/m^3 on average) compared to the Standard Control Condition (106 μg/m^3 on average, $p = .052$; Fig. 5a), a practically significant 20% lower $PM_{2.5}$ concentration. Similarly, $PM_{2.5}$ concentrations 1 h after the start of cooking events in the residential modules were significantly lower in the Advanced Control Condition (52 μg/m^3 on average) versus the Standard Control Condition (69 μg/m^3 on average, $p = .011$; Fig. 5b). Despite the lower $PM_{2.5}$ concentrations, participants reported a greater number of IAQ related complaints during the Advanced Control Condition (average of 16 complaints per participant) relative to the Standard Control Condition (average of 11 complaints per participant; Fig. 6, $p < .001$). The most notable difference between the two conditions was the high number of odor related complaints during the Advanced Control Condition. A likely explanation for these complaints might be the personal control participants had over the stove hood during the Standard Control Condition wherein they could power on the stove hood just before, or as they began, cooking. In the Advanced Control Condition, this control was not present, as the $PM_{2.5}$ threshold had to be reached before the stove hood would power on. Prior research on odor issues has been in the context of mold [41,42] and environmental tobacco smoke (ETS) [43–45], as they critically affect health and can oftentimes be perceived through smell as $PM_{2.5}$ concentrations rise. Yet, unlike mold and ETS odors, cooking related odor complaints in the current study did not show a relationship with $PM_{2.5}$ concentrations. Therefore, while the delay in stove hood operation during the Advanced Control Condition might have led to a higher number in odor related and other complaints, such as smoke, it may be that the lack of being able to control the stove hood made participants more sensitive to IAQ related conditions. More research is needed.

Next, we paired $PM_{2.5}$ concentration during cooking with the IAQ complaints to investigate whether differences in $PM_{2.5}$ concentration might explain these complaints (Fig. 7). We did not separate these analyses by condition and, instead, compiled all IAQ complaints and $PM_{2.5}$ concentrations measured in the kitchen. Analyses revealed $PM_{2.5}$ concentration was significantly higher (81 μg/m^3) at times during which any complaints were made relative to the times when no complaints were made (56 μg/m^3, $p < .001$). Regarding specific IAQ complaints, 'Smoky air' was reported at significantly higher $PM_{2.5}$ concentrations (93 μg/m^3, $p = .002$) versus no complaints of 'Smoky air' (61 μg/m^3). Generally, it appeared that participants made complaints when $PM_{2.5}$ concentrations exceeded ~80 μg/m^3 but made few complaints when $PM_{2.5}$ concentrations were lower than ~60 μg/m^3. These observations are notable given that odor garnered the greatest total number of IAQ complaints but did not demonstrate clear differences by $PM_{2.5}$ concentration. Cooking emissions consist of PM and gaseous components [46, 47], and these emissions take place in parallel. Measuring PM or detecting certain PM levels can serve as a proxy for other components that pollute indoor air. While using TVOC sensors placed in the same sensor array alongside CO_2, temperature, and relative humidity sensors, we could not detect an increase in TVOC. TVOC group consists of over 300 components, and the sensors we used probably were not responsive to the specific TVOC emitted during cooking [24] in the current experimental setup. More research is still necessary to provide deeper

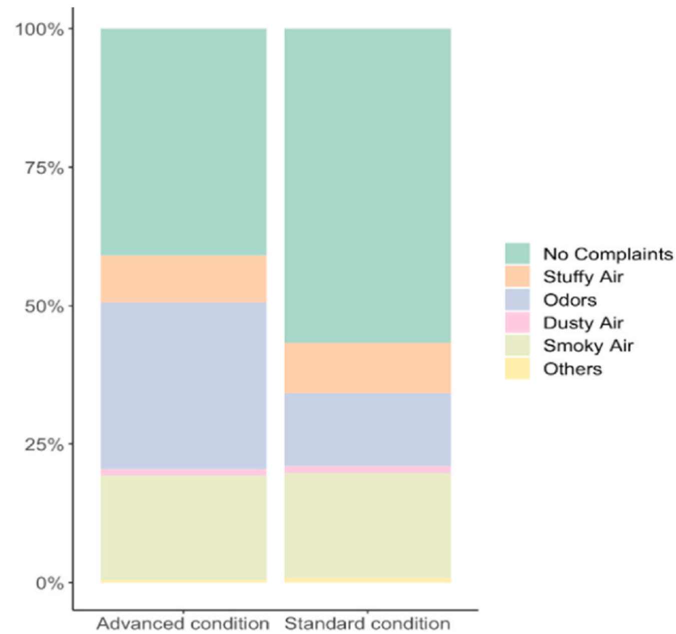

Fig. 6. IAQ complaints breakdown during cooking in the advanced and standard control conditions.

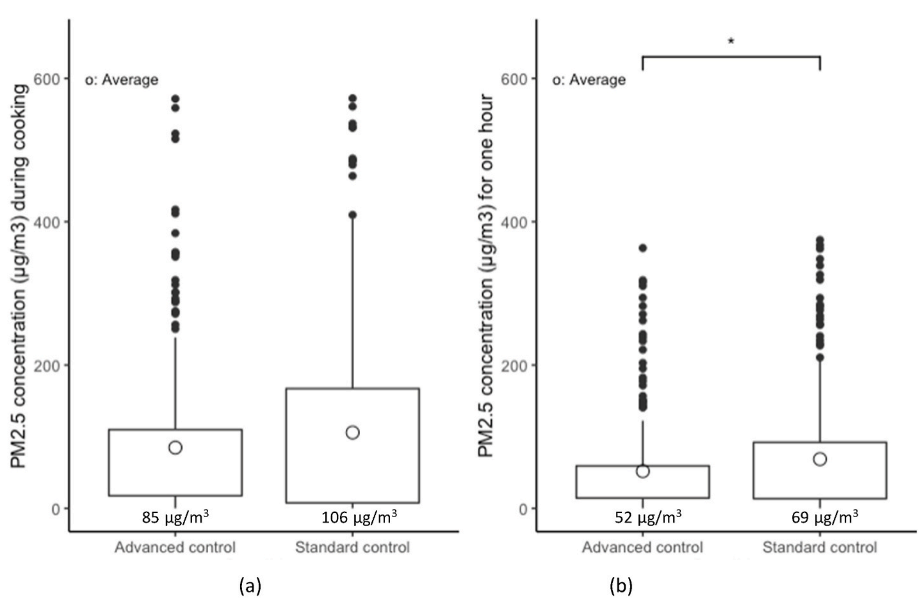

Fig. 5. $PM_{2.5}$ concentrations in the kitchen (a) during cooking and (b) an hour after the start of cooking.

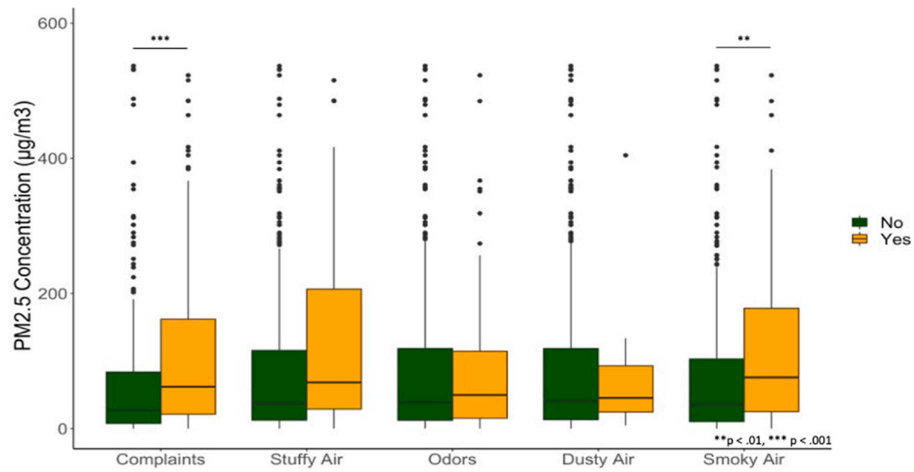

Fig. 7. $PM_{2.5}$ concentration during cooking by complaints.

insight into the relationship between PM and gaseous cooking emissions and human perception of indoor air quality.

These observations suggest further research should be conducted to discern $PM_{2.5}$ thresholds at which individuals start to demonstrate negative perceptions of the IAQ environment—research that could lead to actionable recommendations for how individuals could improve IAQ when they begin making these perceptions. These observations also have implications for current guidelines. For instance, when we compare the $PM_{2.5}$ concentrations at which study participants started to make IAQ complaints, 81–93 μg/m^3, to the WHO exposure guideline of 15 μg/m^3 [48] or U.S. EPA guideline of 35 μg/m^3 [49], we note substantial differences. While short-term and 24 h exposure values cannot be directly compared, the aforementioned difference provides numerical insight into $PM_{2.5}$ exposure and health, clearly demonstrating that IAQ perception may not match with actual $PM_{2.5}$ concentrations [50]. This insight is important for inclusion in future standards regarding IAQ control.

It is important to note that $PM_{2.5}$ concentrations may not be the only driver of complaints related to odor, stuffiness, and/or smokiness. Thermal conditions such as temperature, relative humidity, and air movement also may impact PAQ. For example, studies note more complaints of stuffiness in the summer, presumably due to the higher temperature and/or relative humidity introduced from natural ventilation [50]. Further support is suggested when considering that the better IAQ observed in a green building was not perceived by occupants when the environment was warmer [51]. On the other hand, increased air movement compensated for decreased PAQ and perceived air freshness under warm temperature conditions [52]. In this study, on average, participants had thermally 'Neutral' to 'Satisfied' responses. Thus, it is unlikely that the IAQ complaints observed were attributable to the thermal conditions of the residential modules during each Condition and, instead, were due in part to cooking generated $PM_{2.5}$ concentrations. Again, further research is warranted on the connection between $PM_{2.5}$ concentration and IAQ complaints made by participants to determine possible thresholds for perceivable changes in IAQ and associated IAQ control strategy recommendations.

3.4. Subjective responses on IAQ and $PM_{2.5}$ concentration during cleaning

No differences between conditions were observed for PAQ or odor intensity during cleaning (Fig. 8). On average, PAQ was reported as 'Slightly good' while a 'light odor' intensity was perceived during both conditions. These observations may be related to the far lower $PM_{2.5}$ generation during cleaning activities, with no observable change in $PM_{2.5}$ concentration during 49% of cleaning activities. However, $PM_{2.5}$ concentration during cleaning activities was significantly lower during the Advanced Control (3.55 μg/m^3) versus Standard Control Condition (7.68 μg/m^3, p = .013; Fig. 9). Although statistical significance exists, there is no practical meaning to this difference, and results are within the measurement uncertainty of the device. Notably, the impact of automated IAQ control interventions specifically for cleaning activities may be larger in real-world settings wherein a greater number of occupants stay longer in shared spaces, and where dust and other pollutants may build up over time within carpet fabric due to human and, at times, animal traffic.

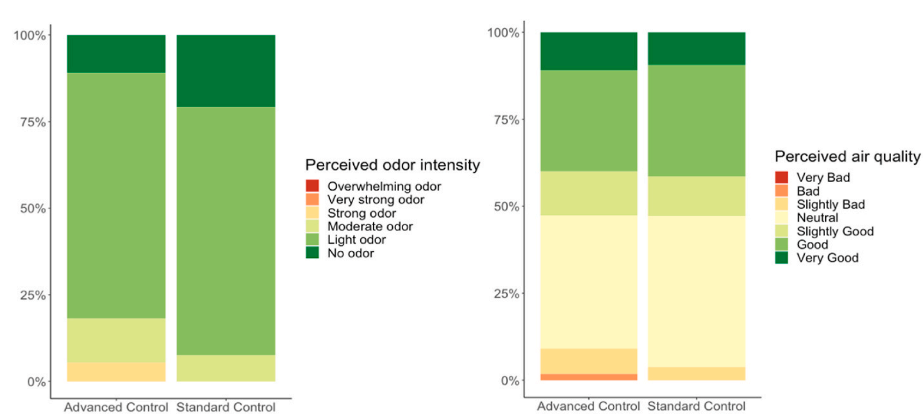

Fig. 8. Perceived odor intensity and air quality during cleaning in the Standard and Advanced Control Conditions.

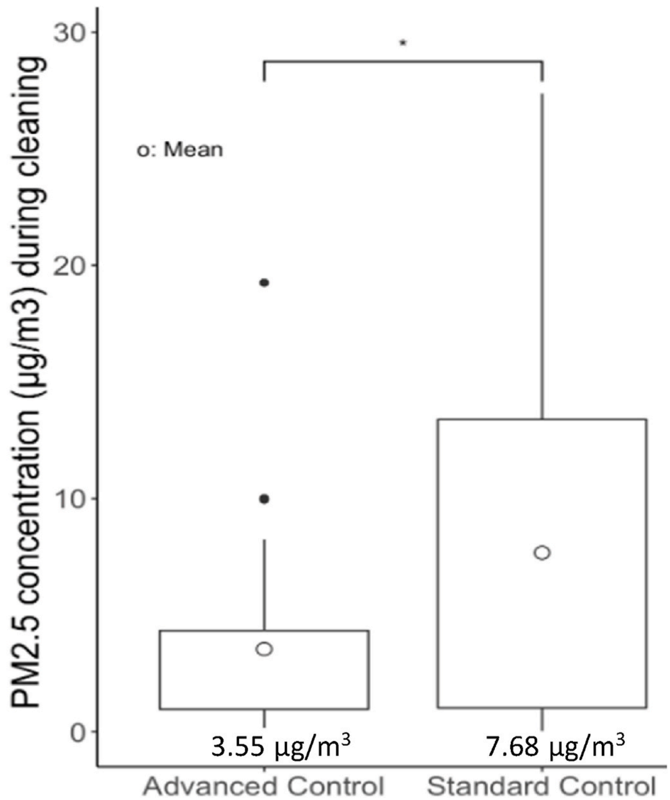

Fig. 9. $PM_{2.5}$ concentration during cleaning in experimental Conditions.

3.5. Relationship between momentary and weekly assessment of subjective IAQ

Since cooking represents the greatest source of indoor pollution [16], it is important to understand what factors influence human perception longer-term (*e.g.,* weekly) versus momentarily. We thus investigated the association between daily IAQ complaints during cooking with overall environmental satisfaction, IAQ satisfaction, PAQ, and IAQ preference responses we collected at the end of each week. As expected, moderate negative correlations were observed between the daily number of IAQ complaints during cooking and weekly overall environmental satisfaction (r = - 0.47, p < .001), IAQ satisfaction (r = - 0.57, p < .001), PAQ (r = - 0.56, p < .001), and IAQ preference (r = - 0.49, p < .001). We completed similar analyses for cleaning activities. Interestingly, momentary assessment of PAQ during cleaning activity was moderately positively correlated with weekly overall environmental satisfaction (r = 0.43, p = .003), IAQ satisfaction (r = 0.47, p < .001), and PAQ (r = 0.46, p = .001), possibly because participants perceived they were improving the 'cleanliness' of their environment. Since longer-term occupant feedback on the environment is based on the "memory" [53], recall bias might explain some of these observations. Future studies should focus on understanding the relationship between short- and longer-term perceptions by employing ecological momentary assessments [22]—a methodology that has been implemented during thermal comfort investigations [54–56] and could be translated to IAQ studies.

3.6. Other subjective responses and measured environmental conditions

Additional questions asked of participants during the study included satisfaction and perceptions related to the thermal, lighting, and acoustic conditions of various environments. The objective of these assessments was to investigate if other environmental quality parameters served as confounding factors between the two conditions and our emphasis on investigating IAQ perceptions. Observations indicated thermal, lighting, and acoustic satisfaction and perceptions were similar between all environments and between the residential modules set up in either condition (Tables 3 and 4), and were, again, unlikely to have confounded our IAQ perception results.

Examining CO_2, TVOC, and relative humidity levels confirmed that these air quality components were unlikely to have confounded our IAQ perception results. First, the CO_2 levels remained at 450 ppm on average across all rooms, with maximum levels of ~740 ppm in the bedroom during the night in both conditions (Fig. 10a). The air exchange rate in the residential module was 1.6 h^{-1} with required ventilation. The details of the air exchange rate with different IAQ interventions can be found in our previous publications [57]. Second, the average TVOC levels remained below 800 ppb for both experimental conditions (Fig. 10b). Lastly, relative humidity was below 60% during the entire study (Fig. 10c). These environmental parameters fall well within the ranges as suggested by the ASHRAE 62.1 Standard [58]and lend credence to the fact that the residential module was unlikely to have had air quality concerns that might have confounded study observations.

WHO has established guidelines [48] for short-term exposure to $PM_{2.5}$, recommending an average threshold of 15 µg/m^3 over the 24-h cycle. While the Occupational Safety and Health Administration (OSHA) sets Permissible Exposure Limits (PELs) for various airborne contaminants that may be present in commercial kitchen environments [59]. It's important to note that these PELs are not specific to commercial kitchens alone but are part of the broader occupational health and safety regulations. OSHA does not have a specific PEL for PM, but it states that exposure to airborne particulates in commercial kitchens should be minimized through proper ventilation and other control measures that are regulated. Although commercial kitchens, from the exposure perspective, represent a different class of environments than domestic kitchens, both don't have specifically defined PEL. This area requires further research on links between exposure and health and translating that research into regulations.

Specifically for domestic kitchens where proper ventilation and control measures are not mandated, relying solely on human senses, such as smell, for air pollution risk assessment and manual operation of air quality interventions for exposure reduction does not often lead to actions that improve indoor air quality [60]. Studies have shown that there is often a disconnect between perceived air quality and actual health risks, leading to underutilization of natural ventilation options [61] in buildings and neglecting the use of air quality interventions such as stove hoods [20] or portable air cleaners [62]. Understanding the human perception of air quality better and determining effective strategies for utilizing air quality interventions to bridge this gap between perception and health risk is crucial.

Table 3
Average satisfaction and perception with thermal, lighting, and acoustic environmental qualities.

		Home	Office	Residential module Standard condition	Residential module Advanced condition
Satisfaction[a]	Air temperature	5.37	5.15	5.80	5.89
	Light level	5.29	4.85	6.08	6.04
	Sound level	5.43	5.00	5.72	5.52
Perception	Air temperature[b]	4.33	4.55	4.40	4.22
	Light level[c]	4.23	4.69	4.84	4.74
	Sound level[d]	3.54	3.69	3.40	3.15

[a] 7-point Likert scale from Very dissatisfied (1) to Very satisfied (7).
[b] 7 -point Likert scale from Hot (1) to Cold (7).
[c] 7 -point Likert scale from Very dark (1) to Very bright (7).
[d] 7 -point Likert scale from Very quiet (1) to Very loud (7).

Table 4
Measured environmental qualities in residential modules.

IEQ components	Temperature (°C)	Relative humidity (%)	CO_2 (ppm)	Illuminance (lux)	Noise (dBA)
Mean ± sd	23.64 ± 1.18	28.23 ± 9.45	447.61 ± 41.28	74 ± 219	43.63 ± 3.48

4. Limitations

Earlier intervention studies that investigated the impact of automated PAC on $PM_{2.5}$ removal compared: (1) sham-mode filtration in which all filters in the PAC were removed, (2) auto-mode filtration in which the PAC was set to auto mode, and (3) adjustable-mode filtration in which the participants were allowed to adjust the PACs manually [63]. Before conducting the study described in this paper, we conducted experiments comparing the performance of ceiling-mounted air supply alone with a combination of ceiling-mounted air supply and automated stove hood, two PACs, and bathroom exhaust. The current study aimed to investigate how using a stove hood manually with a ceiling-mounted air supply compares to using other interventions in combination with automated air quality interventions. To achieve this goal, we compared two conditions with participants. The first condition, the Standard Control Condition, utilized a ceiling-mounted air supply and a manually operated stove hood, a common setup in US homes. The second condition, Advanced Control Condition, involved a combination of ceiling-mounted air supply with an automated stove hood, two PACs, and bathroom exhaust.

During the study design phase, we considered the utilization of sham operation of the stove hood and two PACs. If we implemented that design, we would have to run three conditions: (i) stove hood and 2 PACs in sham mode, (ii) 2 PAC in sham mode and stove hood with filter in manual mode and (iii) full automation of all interventions. From the statistical power perspective, each condition would require two weeks of data collection, substantially increasing the length of our study from four weeks to six weeks. Since we utilize crossover design, we would have to consider 3 conditions and the effect of sequence instead of two, which would require additional subjects. The first condition, with stove hood and two PACs in a sham mode, would represent the case of only ventilation for cooking emission control. As we mentioned above, several research studies, including one of our publications, investigated the impact of ventilation on cooking emission control. We thought that introducing such a complex methodology would not yield enough benefit and we omitted that condition. We recognize this as a limitation of current study, and it is important to note that we relied on measurements to understand the difference between only using a ceiling-mounted air supply and the Advanced Control Condition and didn't include that as our third control condition, but we do not belive this limitation has a crucial impact on the study results.

The survey-based assessment of perceived indoor air quality (IAQ) may have biases and limitations, as people tend to underestimate air quality risks. Another limitation is that the experiment was conducted in a one-bedroom environment without operable windows, which differs from the average single-family house in the U.S., potentially affecting $PM_{2.5}$ concentration distribution. Future studies should consider larger floor areas and natural ventilation in IAQ interventions. Additionally, the study's scope focused solely on $PM_{2.5}$ concentration without considering the chemical composition of emitted particles, which is crucial for including cancer risk based on black carbon analysis in future research.

5. Conclusion

As technology has advanced, numerous smart home and home automation interventions are being explored to improve several aspects of IEQ, including IAQ. Yet, limited studies have assessed the impact of automated IAQ control interventions on occupants' perceptual outcomes during common pollutant-generating household activities such as cooking and cleaning. To reduce cooking and cleaning emitted pollutants, we developed an automated IAQ control intervention based on real-time sensor readings of $PM_{2.5}$ and evaluated the perceptual differences between this Advanced Control Condition and a Standard Control Condition using a crossover study design. Observations suggested that the Advanced Control Condition resulted in ~20 μg/m^3 (~20%) lower $PM_{2.5}$ concentrations during cooking. Further, observations during cooking suggested that participants made IAQ complaints when $PM_{2.5}$ concentrations >~80 μg/m^3 but few complaints when <~60 μg/m^3—indicating the need for additional research on $PM_{2.5}$ thresholds. The results verified that potential thresholds of perceivable $PM_{2.5}$ concentration exist. This critical piece of information is missing from currently available guidelines and standards. WHO health based exposure guidelines state that a 24-h averaged $PM_{2.5}$ concentration should not exceed 15 μg/m^3 [48], while the US EPA suggests a 35 μg/m^3-threshold for 24-h averaged $PM_{2.5}$ concentration [49]. Our observations suggested that participants complained when $PM_{2.5}$ concentration levels reached ~80 μg/m^3. This may indicate that PM levels must be much higher than current guidelines before individuals noticing and taking action to remediate PM levels; thus, advanced IAQ interventions like that within our Automated Control Condition may offer notable benefits at lowering occupant PM exposure. Adding further credence to the importance of advanced IAQ interventions is the fact that noticing unacceptable $PM_{2.5}$ levels during cooking has been shown to not increase individuals' stove hood use given that their behavior is not influenced by health risk perception [60]. Finally, despite the Advanced Control Condition resulting in lower cooking generated $PM_{2.5}$ concentrations versus the Standard Control Condition, this did not enhance weekly IAQ satisfaction and PAQ and only impacted the daily

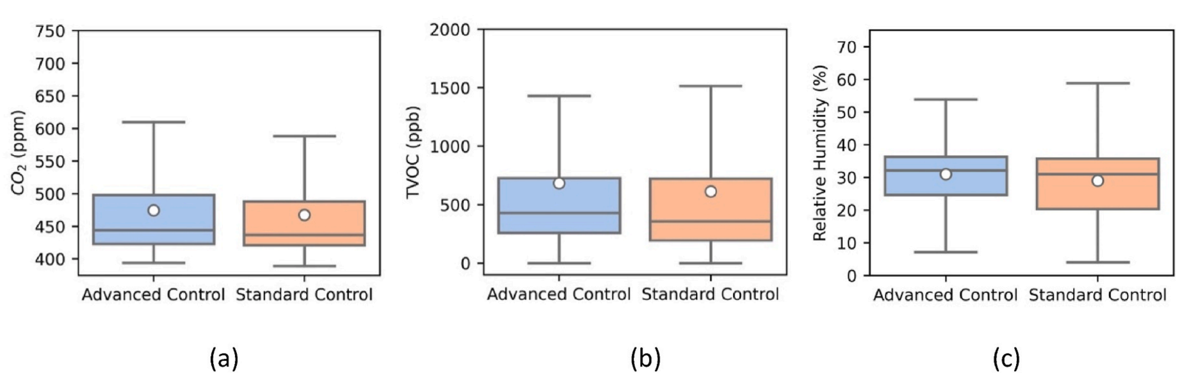

Fig. 10. Other air qualities in the two experimental conditions: (a) CO_2, (b) TVOC, and (c) Relative humidity.

measurements of these perceptual outcomes. Further research is thus warranted, with particular attention on how controllability affects IAQ perception and how more actionable recommendations can be provided to individuals to improve household IAQ, particularly during cooking and cleaning activities, before perceivable negative changes in IAQ occur.

CRediT authorship contribution statement

Young Joo Son: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Validation, Investigation. **Zachary C. Pope:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Jovan Pantelic:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jovan Pantelic reports financial support and equipment, drugs, or supplies were provided by Panasonic Corporation of North America. Jovan Pantelic reports financial support, administrative support, and equipment, drugs, or supplies were provided by Delos Living LLC. Zachary C. Pope reports financial support, administrative support, and equipment, drugs, or supplies were provided by Delos Living LLC. Young Joo Son reports financial support, administrative support, and equipment, drugs, or supplies were provided by Delos Living LLC.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110713.

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