INTRODUCTION

Most people spend a large portion of their early years—when brains, bodies, and destinies are developing—inside the four walls of a classroom. Indoor environmental quality (IEQ) in schools is therefore immensely important, as children are particularly susceptible to detrimental impacts of environmental exposures. IEQ is impacted by pollutants introduced from outside air, such as vehicle exhaust, particularly at schools located near pollution sources, such as highways. There are also a variety of pollutants originating indoors, such as volatile organic compounds, mold, radon, and CO₂ which is generated in all occupied spaces.

Ventilation plays a crucial role in protecting children from indoor pollutants by diluting concentrations with filtered outside air. Inadequate ventilation is thus often a major culprit behind poor IEQ. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62.1 standard and California Title 24 define the minimum ventilation rate (VR) for classrooms as 6.8 and 7.1 L/s per person, respectively. Poor ventilation in schools is common, including California schools. Poor ventilation has...
been demonstrated to negatively affect student health and learning.\textsuperscript{1,7,10,11,12,13,14,15,16,17} For example, Chatzidiakou et al.\textsuperscript{3} found that VRs lower than 8 L/s per person were associated with a higher risk of viral infections and asthma symptoms, as well as diminished concentration and attention span.

The COVID-19 pandemic raises additional concerns because sufficient ventilation is crucial to reduce risks of airborne disease transmission, particularly in densely occupied indoor spaces like classrooms.\textsuperscript{18,19} Dai and Zhao\textsuperscript{20} suggest that reducing transmission risk to 1% in a classroom would require a minimum VR of about 706 cfm (333 L/s) per inch for 3 h of exposure, or about 177 cfm (84 L/s) if masks are worn. Hou et al.\textsuperscript{19} identified 500 ppm as the CO\textsubscript{2} threshold associated with sufficient outdoor ventilation to prevent classroom COVID-19 aerosol spreading. ASHRAE has no requirement to maintain CO\textsubscript{2} levels below a specified concentration, but Chan et al.\textsuperscript{8} estimate that a classroom ventilated at 7 L/s-person (per ASHRAE 62.1 standard) would have a steady-state CO\textsubscript{2} concentration of 1100 ppm.

However, increased ventilation rates have drawbacks including increased exposure to outdoor pollutants as well as potential issues with thermal comfort and energy consumption associated with increased conditioning for heating and cooling outdoor air. Increased ventilation rates can be combined with improved filtration of recirculated air to reduce the probability of long-range airborne infectious disease transmission.\textsuperscript{21} This paper assesses ventilation systems that were designed to meet California’s outdoor air rate code requirement for classrooms of 7 L/s-person, which slightly exceeds ASHRAE standard 62.1 under typical classroom occupancy conditions. It is very important to meet, at minimum, this requirement in the midst of the COVID-19 pandemic.

As schools reopen amidst the pandemic, it is vitally important that classrooms are adequately ventilated to protect the health of students and teachers. It may also be critical to educate teachers about classroom ventilation to instill confidence and support behaviors that complement and do not counteract planned building performance. This research draws on IEQ monitoring and teacher survey data from a study conducted during the 2016–2017 school year of California classrooms to explore teachers’ experiences with classroom heating, ventilation, and air conditioning (HVAC) systems. The study highlights potential non-technical challenges that may arise from or inhibit technical solutions to improve ventilation such as teachers’ use of fan controls and supplementary ventilation strategies.

### 1.1 Study background

The California Energy Commission funded the University of California, Davis, to lead a research project (contract EPC-15-033) that included an HVAC characterization study of 11 schools across the state that had recently replaced single-zone HVAC systems (where single zone refers to one HVAC system per classroom). The study included on-site technical audits, IEQ monitoring, a teacher survey, and interviews with school district facilities staff. This paper reports data from the teacher survey and IEQ monitoring, both of which focused on 104 classrooms across the 11 schools. For full results and detailed technical assessment of HVAC system performance and IEQ, see Pistochini et al.\textsuperscript{22} and Chan et al.\textsuperscript{8}.

The HVAC characterization study found that the new equipment largely failed to deliver code-compliant levels of ventilation (7 L/s-person) for a host of reasons, mainly resulting from a lack of testing, inappropriately adjusting outdoor air rates at the time of installation, and problems with operation and maintenance. Nearly 70% of the classrooms had a mean daily maximum 15-min average CO\textsubscript{2} concentration exceeding 1100 ppm (commensurate with ASHRAE 62.1, per.\textsuperscript{8} Estimated ventilation rates across classrooms had a mean of 5.2 L/s-person (SD = 2.0 L/s-person).

Also worth noting, about 60% of the monitored classrooms had mean temperatures higher than 23°C (73.4°F). Student performance research suggests classroom temperatures lower than 22–23°C are optimal.\textsuperscript{11,17} Twenty-two percent of classrooms were warmer than 78°F for more than 20% of school hours.

Given these findings and the current context of COVID-19, this research revisited data from the California schools HVAC characterization study to address two main questions regarding teacher experience. First, can teachers tell when their rooms are under-ventilated, either by correctly identifying the issue as under-ventilation or through some reliably associated perception (e.g., stuffiness)? If so, there are implications for training teachers how to identify and respond to under-ventilation. If not, this will further highlight the need for proactive measures to ensure adequate ventilation. Second, are teachers taking actions to deal with under-ventilation or related
issues that may improve ventilation or inadvertently worsen it? The answer will have implications for teacher training, allowable/recommended practices, and technical strategies.

1.2 | Classroom ventilation and occupant perceptions

Literature on whether building occupants can reliably perceive under-ventilation is inconclusive. Some studies that compare teacher and student IEQ perceptions with measured VRs (typically estimated from CO2 measurements) suggest that they cannot reliably perceive under-ventilation.23-27 Others have found relationships between lower ventilation and/or higher CO2 concentrations and teacher and/ or student perceptions of poorer air quality in general,17,28 worse air freshness,17,29 greater odor strength25,29 or stuffiness.16 Kinshella et al.30 also found there were more complaints about dryness and dustiness in classrooms where CO2 levels exceeded 1000 ppm for more than 10% of the day.

Dorizas et al.31 were unique in identifying a counterintuitive relationship between higher CO2 and greater satisfaction with indoor air quality, despite also identifying a negative relationship between CO2 and student health and performance. Indoor temperature seemed to be a strong factor influencing satisfaction with air quality: Students in the coolest rooms (median temperature of 22.3°C) were “totally satisfied” with the air quality whereas those in rooms about 25°C, were “totally dissatisfied.” The authors hypothesized that indoor temperature may have been a confounding variable in the observed relationship between CO2 and air quality satisfaction since greater ventilation may have raised indoor temperatures (in cooling season). Similarly, Norbäck and Nordström28 found that maintaining temperatures below 22°C was the dominant factor in teachers’ satisfaction with indoor air quality. Other variables that may lead students and teachers to perceive poor air quality include higher relative humidity,31 higher levels of VOCs, molds, bacteria, and respirable dust; or when buildings do not use a mechanical air supply.27 The present study considered teachers’ perceptions and practices related to all of the above IEQ parameters that have been found to be related to ventilation and perceived air quality.

2 | METHODOLOGY

2.1 | School recruitment

The HVAC characterization study focused on public schools that had within the last three years replaced at least five, single-zone classroom HVAC replacements. Those with more replaced units were prioritized to increase classroom sample size. For inclusion in the study, classrooms had to be typical rather than special-use (such as art or chemistry labs that may exhibit atypical IEQ conditions).

Data from schools’ applications to a California state-funded energy efficiency program (California Clean Energy Jobs Act, Proposition 39, 2013-2017) were used to identify schools (and classrooms) that fit these criteria. In addition, the research team utilized its professional network to identify other qualified schools, including those that did not use the program but had installed HVAC replacements. The research team targeted certain districts to achieve a sample that reflects some of the range of California schools’ characteristics, in terms of district size, population density, region, and average household income. Ultimately, 104 classrooms from 11 schools (6 to 10 classrooms per school) in 9 public school districts were enrolled. Classroom served Kindergarten through 12th grades. Of the 104 classrooms, 68% were permanent construction and 32% were portables, which is also representative of California’s K-12 classrooms.

2.2 | IEQ data collection

In each of the studied classrooms, the research team installed a wall-mounted, laboratory-calibrated, CO2 sensor (Vaisala, Finland) to measure CO2 concentrations by infrared absorption. The CO2 sensor was installed at a location away from doors, windows, and supply air outlets to reflect typical room conditions more accurately. Data loss (e.g., power unplug and bad sensor connection) from 10 classrooms reduced the sample size for CO2 monitoring to 94 classrooms.

The research team also collected data to estimate the duration of heating/cooling use and time with the exterior door open. A HOBO U12 data logger was installed on the grill of the supply air outlets for monitoring supply air temperature and relative humidity. Door open status was measured using a HOBO UX90 state data logger. See Chan et al.8 for full details regarding the IEQ monitoring methodology.

2.3 | Survey recruitment

During field visits to install monitoring equipment, researchers left a letter on the teacher’s desk in each of the 104 classrooms to inform them about the installed equipment and notify them to expect an email about the teacher survey. Seven classrooms were shared by two teachers, both of whom were recruited, for a total of 111 recruited teachers (only the first response for these classrooms was retained to meet the independent observations criterion for statistical tests performed). Teachers’ email addresses were collected from school administrators and staff or school websites.

Emails were sent to teachers on a rolling basis (one school at a time) from October 2016 to June 2017 as the equipment installation was completed. The email provided an informed consent document and invitation to participate in a 15-min survey regarding teachers’ experience with heating, cooling, and ventilation in their classrooms. As an incentive to participate, each teacher was offered a $25 Target Gift Card, delivered via email upon completion of the survey. Up to three weekly reminders following the initial invitation were sent to
teachers to request their participation if they had not yet completed the survey. The survey could be completed in multiple sessions rather than all at once.

After removing responses from any classrooms represented twice as well as those less than 50% complete, the final sample was 84 teachers. The sample size for individual questions was at times lower than 84 because respondents were able to skip questions, and the module on classroom heating was skipped for teachers who had not yet experienced a heating season in their classroom with the newly installed HVAC equipment.

### 2.4 | Survey instrument

The online survey programmed in Qualtrics included primarily closed-ended questions with Likert-style response options, as well as some open-ended questions to elicit more detailed explanations. Questions pertained to teachers’ perceptions and practices related to ventilation and IEQ more broadly, since ventilation interacts with other parameters and occupant perceptions of ventilation may be conflated with these other parameters (e.g., temperature, relative humidity, and odor). IEQ perception questions included overall satisfaction with air quality and overall satisfaction with temperature (response options: Very dissatisfied, Dissatisfied, Neutral, Satisfied, and Very satisfied); the degree to which air quality or temperature interfere with the learning environment (Doesn’t interfere, Interferes a little, and Interferes a lot); and frequency of specific air quality issues: stuffy or stale, drafty, smelly, dusty or dirty, too dry, and too humid (Never, Less than once a month, About once a month, Several times a month, About once a week, Several times a week, and On a daily basis). Questions about ventilation-related practices included how often teachers use the HVAC system, box or floor fans, windows, and doors to circulate or freshen the air in their classroom (Never, Less than once a month, About once a month, Several times a month, About once a week, Several times a week, and On a daily basis); and whether they make efforts to circulate or freshen the air more or less than they would like to (with prompts to explain further). All IEQ perceptions and ventilation-related practices questions were asked separately for heating and cooling seasons.

Several questions were asked just once, independent of season. These included perception of whether classrooms received enough fresh air from the HVAC system alone (Yes or No, with an open-ended comment box and prompt to explain “No” responses); and whether teachers use the HVAC system, fans, doors, or windows for reasons other than to heat, cool, circulate, or freshen the air. Teachers were also asked about the level of noise the HVAC system makes (Quiet, Somewhat noisy, and Very noisy); whether the noise impacts the learning environment (Interferes, Enhances by drowning out distractions, Neither interferes nor enhances), with a follow-up open-ended question to explain further if an impact was indicated; and how often they turn off the HVAC system because of the noise.

### 2.5 | School, teacher, and classroom characteristics

The eleven schools in the study are located across 9 counties in California and 6 of its 16 climate zones (CZ), as Table 1 illustrates. All classrooms were designed to be conditioned and mechanically ventilated by a single-zone packaged HVAC system, an inclusion criterion of the study. Schools 3–6 were monitored during heating season, whereas all others were monitored during cooling and shoulder seasons (heating and/or cooling mode operation was determined based on supply air temperature). Schools 1 and 8–11 were cooling-dominated. Both heating and cooling occurred when schools 2 and 7 were monitored. Although half the schools are in mild climate zones (CZ 3, 6, 8, 10, and 11), natural ventilation was infrequently used, as discussed in the Results section.

Respondent demographics are relatively representative of the population of California teachers. Respondents were predominantly female (77% compared to 73% of the population). They were slightly younger on average (Med = 30–39 years old) compared to the population (Med = 40–49 years old). The sample included teachers of all K-12 grades. Many teachers, particularly for upper grades, taught multiple grades that rotated through the teacher’s classroom.

Based on audit data from all 104 classrooms, occupancy in rooms with constant attendance (namely primary grades where classes do not rotate on a period schedule; n = 45) ranged from 15 to 34 students, with a mean of 27 students (SD = 4). Occupancy in classrooms where students rotated by period (namely middle school and high school grades; n = 77) ranged from 1 (teacher prep period) to 35, with a mean of 26 students (SD = 5). Mean classroom area and volume were 891 sq ft (SD = 65) and 8637 ft³ (SD = 1335), respectively. Classrooms were occupied from 4 to “more than 10” hours per day, with a mode of 8 h.

### 3 | RESULTS

Results are organized in six sections. We first report teachers’ overall assessments of their classroom IEQ, in terms of general satisfaction with air quality and temperature as well as prevalence of specific air quality complaints. We then describe their perceptions of
mechanical ventilation provided by their classroom HVAC systems. Third, we explore relationships between these sets of perceptions and objective measurements of classroom ventilation. The final three sections consider teachers’ experiences with other aspects of the human-building interface related to ventilation: strategies they use to supplement mechanical ventilation and their perceptions of thermostat controls and HVAC fan noise.

3.1 | Teachers’ perceptions of classroom IEQ

In the survey, teachers were asked a series of questions about their perceptions of temperature in cooling and heating seasons, and then another series of questions about their perceptions of air quality during cooling and heating seasons. When rating their satisfaction with classroom temperature and air quality, although more teachers were satisfied than not (Figures 1 and 2), a notable minority reported that each interfered with the learning environment to some degree (Figures 3 and 4). Teachers’ satisfaction levels with temperature and air quality were highly correlated (Table 2). Most teachers reported one or more frequent air quality issue (Table 3), “stuffy or stale” air being the most common.

Open-ended responses revealed more details about temperature and air quality issues, including speculation on potential causes. One theme was the uneven distribution of space conditioning (i.e., poor “mixing”) contributing to thermal discomfort, as the following quotes illustrate:

The HVAC vents blow the air to the front of the room only, so the students in the front are distracted by the cold air while the students in the back are distracted by the heat of the room.

Students sitting directly under [a] vent feel temperature differences much more than [the] rest of [the] room and are constantly complaining (rightfully so). If air was spread/distributed more equally around the room this would not be a problem. When the new more powerful AC unit was installed, the old ventilation pipes and vents remained. They are ... not designed to handle the strength of the new AC unit.

Lack of air circulation was frequently mentioned as a cause of poor air quality, for example, The air does not circulate enough to deal with the mustiness of the room; The unit I have doesn’t really circulate the air as much as I would like. The room gets really dusty quite often. Some mentioned or implied the presence of odors in conjunction with stuffy or stale air, for example, It smells really stale most of the time, not fresh; [it] always feels stuffy and the classroom has a smell; The air seems stuffy and unclean. Several teachers attributed these issues to lack of upkeep of the HVAC system or classrooms more generally, including dirty/dusty vents, old carpet, and bad drainage. A few teachers also expressed that HVAC equipment and supplementary strategies may be inadequate to address the source of some odor sources, for example, students sweating after recess or gym class.

Eight teachers volunteered comments about suspected health impacts of poor air quality in their classroom, for both themselves and their students. Symptoms reported included headaches, dizziness, migraines, allergies (e.g., sneezing and itchy eyes), sinus infections, and impaired cognitive function. One teacher mentioned the spread of viral infections: When one student was sick, it felt like it spread very quickly, and everyone felt sick being stuck in the room together with no air flow. Although health impacts were only mentioned by eight teachers, these teachers reported serious concerns (e.g., illnesses requiring teacher or student absences). It should also be noted that no survey questions explicitly asked about health impacts; the questions that prompted these responses were about how air quality interferes with the learning environment.

3.2 | Teachers’ perceptions of mechanical ventilation

The ASHRAE guidelines on mechanical ventilation are designed to ensure that HVAC systems provide adequate ventilation to classroom occupants without the need for supplemental strategies. The HVAC characterization study of 104 California classrooms (84 of which are represented in this study) found that most of the classrooms were not getting sufficient fresh air from their HVAC system due to installation and maintenance issues (see Chan et al.\(^8\) for details). Generally speaking, teachers seemed to accurately perceive this deficiency; about two-thirds (65%) said their classroom did not get enough fresh air from the HVAC system alone. Those who perceived the HVAC system provided sufficient fresh air were significantly more satisfied with both classroom air quality and temperature compared to those who felt the HVAC system ventilation was insufficient [satisfaction with AQ\textsubscript{cooling} season: \(t(78) = -3.45, p < 0.001\); satisfaction with AQ\textsubscript{heating} season: \(t(75) = -3.55, p < 0.001\); satisfaction with temp\textsubscript{cooling} season: \(t(79) = -2.84, p = 0.006\); satisfaction with temp\textsubscript{heating} season: \(t(75) = -2.66, p = 0.010\).
However, survey data also revealed that teachers seem to have some misperceptions about how mechanical ventilation works (or is intended to work). This is perhaps unsurprising given the general inadequate ventilation in these classrooms. For example, a common perception was that the HVAC system did not deliver fresh air at all, for example:

- We have no access to fresh air in our classrooms.
- The air in the room when the HVAC fan alone is used is not fresh, but is humid and stuffy.

Another perception was that ventilation was only occurring when the air conditioner was on, for example:

- The system would need to be operating in cooling mode at most times to circulate enough fresh air.
- The classroom is almost always stuffy and smelly by the end of the day. The only time this is not the case is if the AC is on all day.

It is unclear to what degree these misperceptions were driven by insufficient mechanical ventilation v. teacher misunderstanding of how the HVAC system works. For example, the above comments came from teachers in classrooms that were getting at least some fresh air, albeit generally below code. However, we cannot disentangle the contribution of HVAC system versus supplemental strategies (e.g., opening doors and windows) to the measured VR.

### 3.3 Relationships between teachers’ perceptions and measured ventilation

Relationships between teacher perceptions of IEQ and monitored CO$_2$ levels, as well as derived VR estimates were explored to determine whether and how ventilation levels may (or may not) impact perceptions. Teacher IEQ perception variables included those summarized above. Monitored IEQ variables included several indices of CO$_2$ levels (ppm): mean and median; and mean highest, median highest, and maximum daily 15-min running average. A per-person ventilation rate (VR) was estimated for each school day using the mass balance model presented in Equation 1, where VR is the ventilation rate per person (L/s-person), $E$ is the CO$_2$ generation rate per person (L/s-person), $C_{15\text{max}}$ is the daily maximum 15-min average classroom CO$_2$ concentration (ppm), and $C_0$ is the outdoor CO$_2$ concentration (ppm), assumed to be 400 ppm.

$$VR = \frac{E}{C_{15\text{max}} - C_0} \tag{1}$$

For the most part, teacher satisfaction with overall air quality did not correlate with ventilation (Table 4). However, ventilation did correlate strongly (and negatively) with satisfaction with classroom
TABLE 2 Correlations between teachers’ satisfaction with classroom temperature and air quality

|                         | Temp. satisfaction cooling season | Temp. satisfaction heating season | AQ satisfaction cooling season | AQ satisfaction heating season |
|-------------------------|----------------------------------|----------------------------------|--------------------------------|--------------------------------|
| Temp. satisfaction      | 1                                | 0.73***                          | 0.42***                        | 0.37***                        |
| heating season          |                                  | 1                                | 0.73***                        | 1                              |
| AQ satisfaction         | 0.42***                          | 0.40***                          |                                |                                |
| cooling season          |                                  |                                  | 0.73***                        | 1                              |
| heating season          |                                  |                                  |                                |                                |

***p < 0.001

TABLE 3 Percentage of teachers with air quality complaints at least several times per week

|                      | Cooling season (N = 81–84) | Heating season (N = 78–79) |
|----------------------|----------------------------|----------------------------|
| Stuffy or stale      | 51%                        | 49%                        |
| Smelly               | 30%                        | 21%                        |
| Dusty or dirty       | 25%                        | 25%                        |
| Draughty             | 16%                        | 10%                        |
| Too dry              | 14%                        | 18%                        |
| Too humid            | 11%                        | 9%                         |
| Any of the above     | 63%                        | 58%                        |

temperature. In summary, teachers in classrooms with better ventilation were less comfortable with classroom temperatures. For example, Figure 5 illustrates a clear, negative relationship between mean VR and satisfaction with temperature. Classrooms where teachers were “very dissatisfied” with the temperature had a 42%–58% higher mean VR than classrooms where teachers reported being “very satisfied.”

Independent t-tests comparing ventilation measures with whether or not teachers reported frequent specific air quality concerns (i.e., a few times per week or on a daily basis) yielded only a few significant findings out of 84 possible relationships (six air quality complaints for each of two seasons, combined with seven VR and CO2 measures). Classrooms where teachers reported frequent issues with “stuffy or stale” or “too humid” air in the cooling season had lower peak CO2 levels than classrooms where teachers did not report frequent issues [often stuffy: t(77) = 3.08, p = 0.003; often humid: t(76) = 1.48, p = 0.005]. However, the small sample size of teachers who reported frequent humidity issues in cooling season (n = 8) limits the validity of the latter finding. Mean and median CO2 were higher in classrooms where teachers reported that dusty or dirty air was a frequent problem in cooling season [Mean CO2: t(76) = −2.33, p = 0.029; Median CO2: t(76) = −2.45, p = 0.023]. There were no relationships found between CO2 levels or VR and frequent issues with smells, dryness, or draughtiness, or with any specific complaint in the heating season.

Counterintuitively, classrooms where teachers reported getting enough fresh air from the HVAC system alone had worse ventilation than those where teachers did not perceive sufficient fresh air from HVAC alone (Figure 6). This trend is notable because it was consistent across all ventilation measurements, but it was typically only marginally significant [mean ppm: t(74) = −2.0, p = 0.049; median ppm: t(74) = −1.7, p = 0.088; mean daily highest 15-min running average ppm: t(74) = −2.0, p = 0.055; median daily highest 15-min running average ppm: t(74) = −2.1, p = 0.041; maximum daily highest 15-min running average ppm: t(74) = −1.9, p = 0.064; mean VR: Not enough M(SD) = 5.2(2.0), Enough M(SD) = 4.7(2.0), t(74) = 1.1, p = 0.288; median VR: Not enough M(SD) = 4.9(2.0), Enough M(SD) = 4.2(2.0), t(74) = 1.4, p = 0.162]. One explanation for this relationship could be that teachers who did not perceive sufficient fresh air from HVAC alone may be more likely to open doors and windows, which is explored in the following section.

3.4 Supplemental ventilation strategies

When asked about non-HVAC strategies they use to improve classroom ventilation, teachers most commonly reported opening exterior doors (Table 5). However, many teachers also noted concerns that kept them from opening doors, including student safety, energy waste, noise or other nuisances coming into the classroom, or school policy. As previously mentioned, leaving doors open is sometimes against school rules. An exception is when teachers are meeting with only one or two students; schools often have a policy requiring teachers to leave the door open under those circumstances. These quotes illustrate teachers’ concerns with leaving the door open:

In order to provide a safe school, I would rather not resort to opening the doors to refresh the air.

The fire marshal does not allow us to keep our doors open so whatever the temperature is we have to suffer through it.

We are not supposed to ever leave our doors open, but sometimes the stuffiness forces us to!

I get told to close the door by maintenance.

I would like to keep my door closed more often to keep in the warmth during cold days or coldness
during hot days. However, the door open ensures that we do not get stuffy.

Most of the time doors and windows create issues with flies, rodents, and squirrels.

The lower incidence of opening windows, compared to the exterior door, for supplemental ventilation (Table 5) is reflective of the lack of operable windows in many classrooms, as well as school policies to keep windows shut. Numerous teachers expressed the desire to have operable windows and/or permission to use them to get fresh air. However, some teachers who were able to open their windows did so less often than they would like because it introduced other nuisances when they opened them (e.g., bugs flying inside and noise) and concern for wasting energy if they could not turn off heating and cooling.

Since quite a few teachers reported frequently opening their exterior classroom door, we examined relationships between this practice and other variables. A significantly greater proportion of teachers who thought their HVAC system did not provide sufficient fresh air reported frequently opening their door during cooling season (60%) compared to those who did think it sufficient (36%) ($\chi^2 = 4.2$, $p = 0.041$); no significant difference in heating season ($\chi^2 = 0.02$, $p = 0.892$). Perhaps as a result, classrooms where teachers reported frequently opening their door in cooling season had better ventilation‡ [Mean CO$_2$: open door $M(SD) = 830(200)$ppm, don’t open door $M(SD) = 999(320)$ppm, $t(77) = 2.77$, $p = 0.008$; Median CO$_2$: open door $M(SD) = 806(240)$ppm, don’t open door $M(SD) = 1039(404)$, $p = 0.01$].

### TABLE 4 Correlations between IEQ perceptions and measured ventilation (N = 73 to 79)

| Perception with AQ | Mean CO$_2$ | Median CO$_2$ | Mean of daily highest 15-min running avg CO$_2$ | Median of daily highest 15-min running avg CO$_2$ | Maximum daily highest 15-min running avg CO$_2$ | Mean VR | Median VR |
|-------------------|-------------|--------------|---------------------------------------------|-----------------------------------------------|---------------------------------------------|---------|-----------|
| Satisfaction with AQ in cooling season | -0.02 | -0.04 | 0.06 | 0.03 | 0.15 | -0.04 | -0.04 |
| Satisfaction with AQ in heating season | 0.01 | 0.00 | 0.06 | 0.03 | 0.10 | 0.02 | 0.01 |
| Satisfaction with temperature in cooling season | -0.09 | -0.05 | -0.17 | -0.16 | 0.30** | 0.16 | 0.18 |
| Perception that AQ interferes with learning in cooling season | -0.12 | -0.10 | -0.15 | -0.14 | -0.22 | 0.12 | 0.14 |
| Perception that AQ interferes with learning in heating season | 0.20 | 0.17 | 0.27* | 0.26* | 0.31** | -0.24* | -0.26* |
| Perception that temp. interferes with learning in cooling season | 0.23* | 0.20 | 0.26* | 0.27* | 0.27* | -0.22 | -0.25* |
| Perception that temp. interferes with learning in heating season | -0.25* | -0.22 | -0.27* | -0.26* | -0.33** | 0.35** | 0.34** |

* $p < 0.05$, ** $p < 0.01$.

![FIGURE 5 Mean VR in relation to teacher satisfaction with temperature](image-url)
to teachers’ perception of whether or not their HVAC system provides their classroom with sufficient fresh air.

\[ t(77) = 3.05, p = 0.003 \]; Mean VR: open door $M(SD) = 5.8(2.0)$, don’t open door $M(SD) = 4.2(1.6)$, $t(77) = -3.75, p < 0.0001$; Median VR: open door $M(SD) = 5.3(2.1)$l/s-person, don’t open door \(M(SD) = 4.0(1.7)\)l/s-person, $t(77) = -3.06, p = 0.003$; no significant differences in heating season. These findings relate to those of the previous section that classrooms where teachers reported sufficient fresh air from the HVAC system had higher CO\(_2\) levels compared to those where teachers did not perceive sufficient fresh air from HVAC alone. However, teachers who opened their door frequently in cooling season were less satisfied with air quality in cooling season \([t(80) = 2.14, p = 0.035]\) but not in heating season \([t(78) = 2.30, p = 0.024]\); no difference in mean percentage of time in ASHRAE comfort zone during monitoring \([80\% \text{ in rooms with teacher control: } 84\%, \text{ in rooms without teacher control: } t(81) = 0.66, p = 0.509]\).

Many teachers expressed frustration with limits on their thermostatic control for several reasons, including the inability to condition effectively or efficiently \(e.g.,\) \textit{This is the first time in 22 years I can't adjust it. It’s a new system... We are hot and stuffy most of the time}, inability to take advantage of passive conditioning \(e.g.,\) \textit{I would like to be able to turn my system off when there is a cool day or the room needs to be aired out}, and inability to condition outside of school hours. Many teachers routinely do preparatory work in their classroom outside school hours (late afternoons and evenings on weekdays as well as weekends), when the HVAC programming assumes unoccupied space. Without autonomy to adjust the temperature during off-hours, some teachers avoid using their classroom at those times while others simply put up with the discomfort.

Relatedly, teachers lacked training on how to use their HVAC controls, both in general \(e.g.,\) \textit{I think it would help if the District gave us a set of instructions on how to use the new system because maybe I’m not using it correctly} and specifically with regard to the HVAC fan \(i.e.,\) uncertainty regarding whether and how they could control it, for example,

\begin{quote}
I do not know how to get fresh air into our classroom.
We need more training with this.
\end{quote}

\begin{quote}
I have no idea how to run the fan in the classroom.
\end{quote}

\begin{quote}
Perhaps I’m not aware of all the options (how to turn on the fan).
\end{quote}

While most teachers had some control over the temperature settings in their classrooms \(within an approved range\), the majority did not have any control over the HVAC fan in their classrooms. This is common in classrooms and is intended to ensure the fan operates continuously during occupied hours in order to achieve code-required VRs. Only 7 teachers’ thermostats offered them direct control of

| Table 5 Percentage of teachers who use each ventilation strategy frequently \(i.e.,\) several times/week or on daily basis |
|-------------------------------------------------|------------------|------------------|
|                     | **Cooling season** | **Heating season** |
| Exterior door       | 51%               | 27%               |
| Interior door       | 20%               | 19%               |
| Window(s)           | 13%               | 9%                |
| Box or standing fan | 13%               | 4%                |
| Any of the above    | 55%               | 43%               |

3.5 Thermostatic Controls

Most classroom thermostats \((85\%)\) allowed for some temperature control, typically allowing the teacher to adjust the set point within a few degrees Fahrenheit. Teachers in these classrooms \((n = 71)\) were more satisfied with classroom temperatures than those without temperature control \((n = 13)\); the difference was significant in the heating season \([\text{no control } M(SD) = 1.5(1.2), \text{ control } M(SD) = 2.3(1.1), \text{ where } 0 = \text{Very Dissatisfied and 2 = Neutral}; t(78) = 2.30, p = 0.024]\) but not in the cooling season \([\text{no control } M(SD) = 1.8(1.2), \text{ control } M(SD) = 2.3(1.1), t(82) = 1.49, p = 0.140]\). There was no significant difference in mean percentage of time in ASHRAE comfort
the fan, independent from the temperature settings. In 20 teachers’ rooms, including 5 of the 7 where teachers had direct fan control, the thermostat was programmed to Auto, which means the fan only automatically runs when the air conditioner or heater runs, rather than continuously, as intended. Teachers in the 15 rooms with HVAC on Auto (but no direct fan control) were theoretically able to adjust the temperature to get the fan to come on or turn off if they had some control over the temperature (which all but one did); however, this was problematic, for example,

We are locked out of the fan control, so we can’t turn that on without changing the temperature of the room. Sometimes we don’t need to change the temperature of the classroom, and that is when we don’t get enough fresh air, usually. [Mean VR: 2.9 l per sec per person]

To capture teachers’ use of fan control when available, respondents were asked, “How often do you adjust (or activate) the HVAC system (or its fan) in order to circulate or freshen the air in your classroom?” During the cooling and heating season, 43% and 38%, respectively, said they adjust the HVAC system at least several times per week for these purposes. Note that these percentages exceed the portion of teachers who actually had the ability to control the HVAC fan either directly or indirectly by turning on the AC or heater (26%). This is consistent with the perception of some teachers that the HVAC system only brings in fresh air when the air conditioning is on.

3.6 | HVAC fan noise

Two-thirds of teachers found the HVAC system somewhat or very noisy, and one-third said the noise interfered with the learning environment in the classroom. A common theme in open-ended responses regarding the disruption caused by HVAC noise was that it made it difficult for students to be heard; this was especially an issue with younger children, English language learners, and soft-spoken students. Teachers had to speak louder and ask students to repeat themselves. These quotes are illustrative of the issues:

The fan never shuts off and is really loud. I cannot hear my students anymore. [This is] directly related to the new units. [The] old blower was much quieter.

I HATE the new system. I cannot hear myself think, I cannot hear the kids share their answers, and it distracts greatly from the learning environment.

I literally cannot hear my students’ responses to questions at times (on a daily basis). ... My throat is sore at the end of the day from speaking loudly.

It is really loud and adds to the noise level in the class. I think it results in students being louder because they unconsciously raise their voice to match or exceed the noise. It also adds to the “buzz” level/frenetic feel to the classroom. It makes my class (a loud group even on the best days) even less calm than it already is and adds to my stress level.

4 | DISCUSSION

This study examined California K-12 teachers’ perceptions and practices related to classroom ventilation. Teachers conveyed a desire for more training on their classroom HVAC systems, and ventilation in particular. Misperceptions about the way ventilation works were common, including that the HVAC system does not bring in fresh air. There was also confusion about the controls, including whether and how teachers could control the HVAC fan. These experiences do not bode well for instilling confidence among teachers working in the classroom during the COVID-19 pandemic. Educating teachers about the HVAC ventilation system will promote acceptance of the system despite its nuisances. Future work should develop training materials for teachers that explain the HVAC system in general and particularly explain how mechanical ventilation works and its role in maintaining a healthy classroom.

Of paramount importance is improving the effectiveness of classroom ventilation systems so that they do indeed protect staff and students by mitigating the risk of infectious disease transmission. HVAC system noise also needs to be addressed as many teachers in this study reported that the HVAC noise was detrimental to learning and the overall classroom experience. While students and teachers are wearing masks in classrooms, the noise problem may be compounded. New acoustic strategies, such as a microphone for the teacher, may be warranted even if engineers can devise quieter systems.

Some teachers were frustrated that they could not control the HVAC fan (e.g., turn it off due to noise), and teachers who had some control of their temperature set points were more satisfied with classroom temperature than those without control. Allowing all teachers some control over their thermostat set point and increasing the range of the allowable set point is likely to improve comfort and satisfaction. It is well-documented that perceived control over environmental conditions leads to increased satisfaction.33-37 Educating teachers about the importance of the fan running continuously during class time to ensure adequate ventilation may promote acceptance of the fan despite lack of control, however, additional strategies should be considered to give teachers a sense of autonomy. For example, outfitting classrooms with CO₂ monitors and training teachers to interpret the data and respond appropriately (e.g., report an issue to administration, open doors, and windows to improve ventilation when needed) could foster a sense of control by including teachers in the ventilation feedback loop. This strategy could also maximize transparency and increase teacher confidence in the adequacy of their ventilation systems.
For the most part, teachers did not seem to accurately perceive mechanical ventilation sufficiency. Although the majority did report a lack of sufficient ventilation from HVAC alone, which was in fact quite common, there was generally a lack of correlation between measured ventilation and teachers’ satisfaction with classroom air quality, and no compelling evidence of relationships between poor ventilation and specific air quality complaints. Moreover, those who perceived adequate ventilation from their classroom HVAC system, though more satisfied with both air quality and temperature, actually had worse classroom ventilation.

Many teachers, particularly those who were not satisfied with HVAC system ventilation, frequently opened their exterior classroom door to improve ventilation. There was some evidence that those who engaged in this practice had better classroom ventilation, but they were less satisfied with air quality than those who did not open their door frequently. Chan et al.8 found no relationship between door state (per sensor data rather than teacher report) and ventilation. However, the door sensor data can be imprecise (e.g., a door left ajar 1 inch will register as open), so it may be that teacher report in this case is more accurate than monitored data.

This study also provides some evidence that air quality and temperature can be conflated in occupant perceptions of IEQ. Teachers’ satisfaction with air quality and temperature were highly correlated, and teachers were more often “neutral” in assessing air quality, suggesting less confidence. This may actually contribute to inaccurate perceptions of air quality based on thermal comfort (i.e., if thermal comfort is low, occupants may perceive poor air quality, and if thermal comfort is high, they may be inclined to think air quality is good).

Moreover, study findings point to a potential phenomenon whereby the mechanics of HVAC ventilation could actually be responsible for a negative relationship between ventilation and thermal comfort. Teachers in classrooms with worse ventilation were more satisfied with classroom temperature, consistent with Dorizas et al.31. When the supply fan for the HVAC system is running continuously as designed to provide ventilation, outdoor air (cold in winter and hot in summer) is continuously supplied to the space as a fraction of the supply air. In a classroom that is adequately ventilated, the outdoor air fraction is approximately 30%-50%. The heating or cooling then cycles on and off to meet the room temperature set point. When the heating and cooling are off, the supply air temperature may be uncomfortable in a classroom with adequate ventilation, blowing air colder than the room temperature in winter and warmer than the room temperature in summer. Occupants near the vents are exposed to temperature swings and drafts, which may adversely affect their thermal comfort. Increasing ventilation rates also increases the required heating and cooling, meaning that the cooling or heating cycles per hour increase, which also may adversely affect the comfort of those near vents. This explanation is supported by comments from participants about the discomfort of students near vents. The variation in supply air temperatures resulting from fluctuating outside air temperatures and compressor cycling could be improved with engineering solutions, such as variable speed compressor technology that can modulate the amount of heating and cooling provided and continuously provide consistent supply air temperatures.

These findings suggest that some teachers may perceive that air quality has worsened when they return to classrooms where ventilation has actually been improved to combat COVID-19 transmission. This again points to the importance of CO₂ monitoring and teacher training on HVAC systems. Future research should rigorously model the relationships between IEQ perceptions and VRs, including to better understand the potential for conflation of temperature and air quality in occupants’ IEQ perceptions. It would also be useful to replicate this research to determine whether and how teachers’ knowledge and attitudes regarding ventilation have changed as a result of the pandemic.

5 | CONCLUSION

This research suggests that technical solutions for improved ventilation in schools, although absolutely critical may not be sufficient to support teachers’ confidence in the safety of their classrooms in the midst of the COVID-19 pandemic. Improved ventilation will not automatically be perceived as such, and in some cases teachers may feel their classroom air quality has worsened given the tendency to conflate temperature and air quality. HVAC system noise, already a major problem in many classrooms, will be even more detrimental when combined with mask wearing. When designing more effective ventilation systems, noise reduction should be a priority. Schools should also consider audio supports and practices to ensure students and teachers can hear each other and get sufficient breaks from noise. Classroom CO₂ monitoring and teacher training on how mechanical ventilation systems work are vital to ensure that teachers feel safe returning to the classroom during the pandemic and empowered to protect the health of themselves and their students.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Angela Sanguinetti contributed to conceptualization, methodology, investigation, formal analysis, visualization, and writing—original draft. Sarah Outcault contributed to methodology, investigation, data curation, writing—review and editing, project administration, and funding acquisition. Theresa Pistochini contributed to data curation, writing—review and editing, visualization, supervision, and funding acquisition. Madison Hoffacker contributed to investigation.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES
† Monitoring took place over four weeks at each school, but at different times (cooling season, heating season, and/or shoulder seasons depending on the school).
‡ 30% of California K-12 classrooms are portables according to California Environmental Health Conditions in California’s Portable Classrooms. November 2004. https://ww2.arb.ca.gov/sites/default/files/2020-05/pcs_r2l.pdf

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