A DATA-DRIVEN STUDY ON THE ASSOCIATION OF CLASSROOMS' INDOOR AIR QUALITY, THERMAL ENVIRONMENT, AND STUDENTS' ACADEMIC PERFORMANCE

by

Adel Kabirikopaei

A DISSERTATION

Presented to the Faculty of

Durham School of Architectural Engineering and Construction

University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Architectural Engineering

Under the Supervision of Professor Josephine Lau

Lincoln, Nebraska

May 2021

A DATA-DRIVEN STUDY ON THE ASSOCIATION OF CLASSROOMS' INDOOR AIR QUALITY, THERMAL ENVIRONMENT, AND STUDENTS' ACADEMIC PERFORMANCE

Adel Kabirikopaei, Ph.D.

University of Nebraska, 2021

Advisor: Josephine Lau

Indoor air quality (IAQ) and thermal environment factors of 220 classrooms in the United States midwestern region were measured during two academic years in three seasons and during occupied and unoccupied periods. Measurements during occupied times included indoor CO_2 and formaldehyde concentrations, coarse and fine particle counts, temperature, relative humidity, and globe temperature. Unoccupied measurements consisted of air velocity, carbon monoxide, nitrogen dioxide, ozone, and total volatile organic compounds (TVOC). Student-level data for 1468 elementary students and 1239 middle and high school students related to socioeconomic background and academic performance were also collected. This dataset included gender, ethnicity, lunch-pay status, English language learners, mathematics, and reading scores.

To calculate ventilation rates from the collected CO_2 data, three main methods were used: (1) steady-state; (2) decay rate; and (3) build-up. An uncertainty analysis was performed for all three methods. The study shows that the steady-state method has the least uncertainty in ventilation rate calculations, while the decay and build-up methods had the lowest and highest values for ventilation rates, respectively.

To investigate if classrooms' IAQ and thermal factors vary on the classroom level or the school level, an analysis of variance (ANOVA) was performed. Based on the results, in the schools with multi-zone systems, fewer measurements for CO_2 concentrations, coarse particles, and air velocity measurements (in school-level) may be sufficient to represent the condition of the school. Finally, a multilevel model was used to investigate the associations between IAQ, thermal data, and students' scores using demographic and performance variables as controls. The results revealed associations between student scores and ventilation rates, globe temperature, temperature, fine particle counts concentrations. There are also interaction effects between demographic, performance variables, and IAQ, thermal variables in the classroom.

This research will provide information to school districts and design engineers. The results of this study can be adopted to design experiments for causality relationships and to confirm the effects of IAQ, Thermal environment factors on student academic performance.

Acknowledgments

I’m highly thankful to all the people help me during my journey at the University of Nebraska-Lincoln. First and foremost I am extremely grateful to my academic advisor and committee chair Dr. Josephine Lau for her continuous support and patience during my Ph.D. program. In the last four years, she enthusiastically dedicated her time to help me progress in my research. I also thank other committee members for their useful comments and effort on my research study.

I’m thankful to all members of the School Environmental Effects on Student Achievement (SEESA) research team especially Dr. Lily Wang for her support and Michael Kuhlenengel for his help to collect data in my study.

Finally, I would like to express my gratitude to my parents and my wife. My parents always encouraging me to pursue my dreams and my wife for always being patient and supportive. Without my family’s tremendous understanding and encouragement in the past few years, it would be impossible for me to complete my study.

Table of Contents

Chapter 1. Introduction 1

1.1. Academic Performance and student's demographic 2

1.2. Academic Performance and IAQ 3

1.3. Purpose and Significance 4

1.4. Research questions 6

Chapter 2. Literature Review 8

2.1. Literature Selection Criteria 8

2.2. IAQ in Schools & Student's Performance 9

2.2.1. Ventilation Rates 12

2.2.2. Temperature 18

2.2.3. Particulate Matter 22

2.2.4. Total Volatile Organic Compounds (TVOCs) 24

2.2.5. Formaldehyde 25

2.2.6. Ozone 27

2.2.7. Nitrogen Dioxide 29

2.2.8. Carbon Monoxide 30

2.3. Academic achievement and demographic 30

2.4. Conclusion and future research 33

Chapter 3. Methodology 35

3.1. Classroom's data 35

3.2. Classroom Environmental Data Sampling 37

3.2.1 Indoor Air Quality (IAQ) & Thermal Comfort 38

3.3. Student Data 40

3.4. Data Cleaning ... 45
3.5. Research Question 1 (ventilation rate estimations) ... 46
3.5.1. Steady-state ... 47
3.5.2. Decay ... 48
3.5.3. Build-up ... 50
3.5.4. CO2 generation rate ... 52
3.5.5 Uncertainty analysis (error propagation) ... 53
3.6. Research Question 2 ... 55
3.6.1. Analysis of variance (ANOVA) ... 55
3.7. Feature selection ... 55
3.8. Research Question 3 ... 56
3.8.1. Hierarchical linear modeling (HLM) ... 56
3.8.2. Statistical models ... 59
Chapter 4. Results & Discussion ... 63
4.1. Results (Research Question 1) ... 63
4.2. Discussion (Research Question 1) ... 68
4.3. Results (Research Question 2) ... 71
4.3.3.Analysis of Variance (ANOVA): ... 72
4.4.Discussion Research Question 2 ... 77
4.5. Results (Feature Selection) ... 79
4.5.1. Correlation study ... 79
4.5.2. Omnibus test ... 88
4.6. Results (Research Question 3) ... 90
4.6.1. Elementary Schools ... 90

4.6.2. Middle/ High Schools 95
4.7. Discussion (Research Question 3) 99
4.7.1. Mechanical Systems 100
4.7.2. Ventilation Rates 102
4.7.3. Particles 106
4.7.4. Temperature 107
4.7.5. Globe Temperature 110
4.7.6. Air Velocity 112
4.7.7. Relative Humidity, water damage, odor, and mold 117
4.7.8. Other factors from the unoccupied measurements 118
4.7.9. Recommendations for Future Studies 119
5. Conclusion 121
References 124
APPENDIX A- Correlation study for seasonal IAQ and TC variables 137
APPENDIX B- Interaction plots for demographics and IAQ, TC variables 145
APPENDIX C- Statistical models without performance variables 147
APPENDIX D- IAQ, TC data (the distribution of variables) 151

List of Tables

Table 1. Hypothesis and necessary conditions 6
Table 2. Previous studies and the method and range of estimated VRs in classrooms with mechanical systems 15
Table 3. Previous studies on the relationship between classroom's ventilation rates and student's academic achievement 17
Table 4. Previous studies on the relationship between temperature and student's academic achievement 21
Table 5. Exposure limits set by different standards 26
Table 6. classrooms' flooring and ceiling materials 36
Table 7. The number of mechanical systems in classrooms 37
Table 8. summary of demographic groups in elementary schools and middle-high schools 41
Table 9. CO_2 generation rate adopted in this study per age range 52
Table 10. Measured variables used in the estimation of VR for each method 54
Table 11.Binary values for demographic and performance variables 61
Table 12. Order of the effect of each variable on the uncertainty (highest to lowest)...... 67
Table 13. Correlation study for unoccupied measurements 87
Table 14. Input variables used to build the statistical model (continuous variables) 89
Table 15. Elementary Schools (Reading Scores) 92
Table 16. Elementary Schools (Mathematics Scores) 94
Table 17. Middle/ High Schools (Reading Scores) 96
Table 18. Middle/ High Schools (Mathematics Scores) 98
Table 19. Number of classrooms identified with damage(stain), mold, and odor in each season 117

List of Figures

Figure 1. Number of classrooms in each grade in the sample 35
Figure 2. Sample of measured classrooms 36
Figure 3. CO_2 sensor deployed near supply diffusers 39
Figure 4. The range of mathematics and reading scores (percentile rank) for elementary school students 40
Figure 5. The range of mathematics and reading scores (percentile rank) for middle-high school students 41
Figure 6.. Number of male and female students in elementary and middle-high school classrooms (grouped by grade) 42
Figure 7. Number of free-reduced lunch students in elementary and middle-high school classrooms (grouped by grade) 43
Figure 8. Number of English language learners in elementary and middle-high school classrooms (grouped by grade) 44
Figure 9. Number of white & not-white students in elementary and middle-high school classrooms (grouped by grade) 45
Figure 10. Steady-state method VR estimation for a particular classroom in this study.. 48
Figure 11. Decay method VR estimation for a particular classroom 50
Figure 12. Build-up method VR estimation for a particular classroom 51
Figure 13. Illustration of a typical CO_2 concentration profile in classrooms over a 36-hour period 63
Figure 14. Average CO_2 concentration during occupied hours 64
Figure 15. The range of VR and uncertainty (after eliminating outliers) by three methods in three seasons: (a)winter, (b) spring, (c) fall 65
Figure 16. VRs in different seasons by three methods 66
Figure 17. comparison of single zone and multizone estimated VRs with three methods. 68
Figure 18. The range of seasonal ventilation rates in each school.................................. 74
Figure 19. The range of seasonal globe temperatures in each school.............................. 75
Figure 20. The range of seasonal temperatures in each school.. 76

Figure 21. The range of seasonal fine particles in each school 77
Figure 22. Ventilation rate range and correlations in three season.................................. 81
Figure 23. Globe temperatures range and correlations in three seasons........................... 81
Figure 24. Classrooms' indoor temperature ranges and correlations in three seasons..... 83
Figure 25. Classrooms' fine particels ranges and correlations in three seasons............... 85
Figure 26. Classrooms' relative humidity ranges and correlations in three seasons…….86
Figure 27. The range of elementary students math and reading scores for each mechanical system type.. 100
Figure 28. The range of middle/ high school students mathematics and reading scores for each mechanical system type 101
Figure 29. Ventilation rate range in elementary classrooms in different seasons 103
Figure 30. The range of ventilation rates in three seasons in middle/ high schools 104
Figure 31. Range of free-reduced lunch (FRL) students scores comparing to other students 105
Figure 32. Classrooms air temperature range in elementary classrooms in different seasons 108
Figure 33. Classrooms air temperature range in middle/ high schools in different seasons 109
Figure 34. Classrooms globe temperature range in elementary schools in different seasons 111
Figure 35. Classrooms globe temperature range in middle/ high schools in different seasons 112
Figure 36. Classrooms air velocity range in elementary schools in different seasons ... 113
Figure 37. Classrooms air velocity range in middle/ high schools in different seasons. 114
Figure 38. The range of air velocity in classrooms... 116

Chapter 1. Introduction

More than 50 million students are attending elementary, middle, and high schools across the United States (U.S. Department of Education). On average, Most American children spend around 180 days a year and each day more than 6 hours in the schools (U.S. Department of Education). Student's exposure to indoor pollutants in classrooms may impair their ability to learn and their academic performance. Poor academic performance may affect a student's motivation and even drop out of school.

The U.S. Environmental Protection Agency (EPA) studies show that people are exposed to higher levels of indoor pollutants, which may be two to five times higher than outdoor pollutants (EPA, 1987). In recent years EPA awarded several research projects to investigate K-12 educational indoor environments to maximize student's learning and performance (EPA, 2015). The University of Nebraska - Lincoln is one of seven grantees under EPA's Healthy School STAR program to examine indoor environmental factors and their effects on the scholastic achievement of K-12 students (Wang, 2015).

According to the National Institute for Occupational Safety and Health (NIOSH), indoor environmental quality (IEQ) refers to the quality of a building's environment in relation to the health and wellbeing of the occupants (NIOSH website). IEQ is determined by many factors, including acoustics, Indoor Air Quality (IAQ), thermal comfort, lighting, and damp conditions however, most of the previous research (U. Haverinen-Shaughnessy et al., 2011a; Ulla Haverinen-Shaughnessy et al., 2015; Mendell et al., 2016; Wargocki et al., 2019, 2020) focused on a limited number of factors in a specific area. limited to the assessment of a specific number of IAQ factors in classrooms however, there are additional factors that influence the IAQ and thermal environment of classrooms.

Improving student's academic achievement is the goal of an effective educational system. Student's academic achievement is influenced by a variety of individual and environmental factors. Student's backgrounds and classroom environmental conditions contribute to student's achievement greatly. Having a clear understanding of major significant factors can help policymakers to take effective decisions to improve student's performance. The diverse factors involving in student's academic achievement, reveals the necessity of conducting multidisciplinary studies in this area.

1.1. Academic Performance and student's demographic

In fall 2014, for the first time the number of black, Hispanic, Asian, and Native American students made the majority of students in American schools (U.S. Department of Education). According to the U.S. Department of education in fall 2016, 9.6 percent of public-school students in the United States are English Language Learners (ELL) (U.S. Department of Education, National Center for Education Statistics). In recent years the population of the United States has been even more diverse which results in more diversity in classrooms across the country. This diversity in American schools reveals the necessity of considering demographic information in research studies.

The schools track the performance of students based on different demographic groups. Studying these performance data shows achievement gaps between students with different races. This achievement gap becomes one of the greatest challenges in American classrooms (Bainbridge & Lesley, 2002). Several social and economic factors account for different test scores among students. Disaggregating data regarding gender, ethnicity, socioeconomic status, and home language is a common practice when reporting students' performance (Clarkson, 2008). There are a number of studies on the relationship between gender, students' race; African American, Hispanic American, Asian American, and European American (white) and academic scores. It has been found that ethnicity and gender contribute significantly to mathematics scores (Peng & Hall, 1995) however, in more recent research studies there is not an agreement in the effectiveness of gender in mathematics scores anymore. Having measurement data combined by demographic data help researchers to control data by an individual's specific information.

1.2. Academic Performance and IAQ

Children spend a significant amount of time in classrooms to learn. There is evidence that IAQ conditions in classrooms may affect a student's health and academic performance (Mendell & Heath, 2005; Shendell et al., 2004a). There are numerous studies on the relationship between IAQ factors and student's performance. According to the studies in Europe and the US, student's academic performance has a relationship with the classroom's ventilation rate and indoor temperature (U. Haverinen-Shaughnessy et al., 2011a; Ulla Haverinen-Shaughnessy et al., 2015; Toyinbo et al., 2016). Stafford found that IAQ-renovations resulted in improved standardized math and reading test scores

(Stafford, 2015). Wargocki et.al concluded indoor air factors (CO_2, temperature, and ventilation rate) have a substantial influence on the learning process of the students (Wargocki & Wyon, 2013). Students have a more positive perception in classrooms with adequate ventilation rates (Gao et al., 2014) and Inadequate ventilation rates have a negative impact on the speed of student's mathematical tasks (Bakó-biró et al., 2012).

Previous work on how IAQ and thermal conditions in K-12 classrooms impact student achievement and health have often focused on only one or two factors. Much of that work has shown that these assorted IAQ, thermal conditions, when studied in isolation, can impact student performance and/or health, often documented by absenteeism. Based on the author's knowledge most IAQ, thermal environment and performance studies have been conducted on school's, used classroom's aggregated data, which limits the study to school or classroom level data, ignoring individual student's variations.

1.3. Purpose and Significance

The objective of this study is to investigate the impacts of IAQ and thermal environment factors on students' academic achievement. There is a small amount of research on the relationship between student demographics and academic achievement (Marks, 2016; Thiele et al., 2016). Most studies at schools focused on the satisfaction of occupants with IAQ, thermal factors, ignoring social, phycological aspects (Sadick & Issa, 2017).

In this study, the link between IAQ, thermal factors and student scores across different demographic groups is investigated. The thermal, indoor air quality (IAQ) together with demographic data from 220 classrooms in the Midwest region of the United States, were studied. The IAQ, thermal data have been collected in classroom levels and students' achievement data have been collected at the student level.

Based on the authors' knowledge, there is a limited number of studies on the relationship between IAQ, thermal factors and academic performance which considers socioeconomic variables. This study will broaden the assessment of IAQ, thermal conditions of classrooms in relation to academic performance while considering student demographics. Primarily it is hypothesized that IAQ, thermal factors may influence student scores controlled by their demographics (Table 1). IAQ and thermal factors may impact specific groups of students, which may vary by classrooms and schools.

Most previous studies have been limited to classroom aggregated data, however, in this study three levels of data (student-level, classroom-level, and school-level) are examined. Student-level analysis of performance helps to classify students based on demographics, while the IAQ, thermal data are considered classroom-level data. This leads to our research questions.

Table 1. Hypothesis and necessary conditions

	Hypothesis
1	IAQ, thermal factors are related to student mathematics and reading scores.
2	Socioeconomic status (gender, lunch-pay status, ethnicity) moderates the relationships between the IAQ, thermal factors, and academic scores.
	Conditions
1	There is systematic group variance in scores.
2	The variance in the student-level intercept is predicted by the classroom's IAQ, thermal and school data
3	The variance in the student-level slope is predicted by the classroom's IAQ, thermal and school data.

1.4. Research questions

The following research questions will be addressed in this study:

1. How different the ventilation rate estimations based on various CO_2-based methods? Which method has the least uncertainty for estimating ventilation rates in classrooms?

2. Do indoor air quality, thermal environmental factors vary on the classroom level or the variations are limited to the school level?

3. What are the associations between indoor air quality, thermal environmental factors, and student's academic achievement in different demographic groups?

3.1. Do high-performing and low-performing students respond to IAQ, thermal similarly?

3.2 Do students in different demographic groups respond differently to IAQ, thermal factors?

This study discusses a recent investigation that involves measurements encompassing the thermal, and indoor air quality conditions in K-12 classrooms and tying those to classroom student-level performance on standardized achievement tests while controlling for student demographics. The research seeks to establish how these IAQ and thermal conditions in K-12 school buildings interactively affect student achievement. This research will provide a better understanding of how multiple aspects of the built environment impact student achievement, across a wide spectrum of classrooms and varying demographics.

The results can be applied to new research by including the significant factors in this study to confirm the causality of IAQ, thermal factors on student performance. This research will provide information to school districts and design engineers who are interested in improving the school environment for better student performance. Armed with such results, school districts with limited funds will be able to make more well-informed decisions on how to improve their infrastructure to most impact student achievement.

Chapter 2. Literature Review

In this chapter, studies on classrooms' IAQ and thermal factors that are associated with students' performance in addition to studies on academic achievement and students' demographics were reviewed. For each IAQ and thermal factor, related studies are discussed in separate sections.

2.1. Literature Selection Criteria

Papers on IAQ, theraml factors and their associations with students' academic achievement were selected by searches using google scholar and science direct. Search keywords consist of various combinations of school, classroom, student, indoor air quality, performance, academic achievement, and demographics. Titles and abstracts of papers reviewed to identify relevant papers. Relevant papers were fully reviewed and a summary of the methodology and the results were provided. References of papers that were highly relevant to the study were also reviewed.

The second round of literature review focused on each IAQ, theraml factors in the classroom. Search keywords in this round include school, classroom, student, ventilation, CO_2, particles, temperature, globe temperature, relative humidity, ozone, velocity, TVOC, NO_2, and CO. For those variables with few studies on the association with students' performance, descriptive studies in school environments were added to the literature. In total 143 references were used in this study.

2.2. IAQ in Schools & Student's Performance

Indoor Air Quality (IAQ) refers to the air quality in buildings, which is related to the health and comfort of occupants (U.S. EPA, 2020b). Improving IAQ and controlling contaminants will reduce the risk of health concerns in schools. Due to the potential impacts that poor IAQ might have on student's health and learning, the school's IAQ is a concern for lawmakers and organizations. United States Environmental Protection Agency (EPA) releases guidelines and conducted healthy school programs as well as providing tools to assess IAQ in schools. The National Institute of Occupational Safety and Health (NIOSH), has provided an IAQ self-inspection checklist to address IAQ issues in school districts. IAQ management practices have been done by U.S. schools to implement these guidelines and tools. A study on the implementation of IAQ programs across U.S. schools shows that effective IAQ policies and procedures improve the learning environment for U.S. schoolchildren (Moglia et al., 2006).

Results of a study by Bluyssen et.al in 54 classrooms in the Netherlands show that 87% of students were bothered by noise, 63% by smells, and 42% by sunlight (shining) and 35% by temperature (Bluyssen et al., 2018). In a later study 335 primary school children participated in a workshop in which they were asked to think about their own classroom's IEQ problems. 58% reported noise related problems, followed by 53% temperature, 22% air and 16% light (Bluyssen et al., 2020).

There are several indoor and outdoor factors that influence the level of contaminants and the quality of air in classrooms. For example, the location of the schools can increase their exposure to pollutants or wall coverages and coatings can reduce the release of contaminants (formaldehyde) in the classroom's air (Salthammer, 2019). According to a study in Michigan, schools located in highly polluted areas have the highest proportions of students failing in the state's educational test (Mohai et al., 2011). Chan et.al conducted a study in California schools to investigate why many recent HVAC retrofits are not delivering sufficient ventilation. In this study, 104 classrooms form 11 schools were visited after being retrofitted with new heating, ventilation, and air-conditioning (HVAC) units. Poor system selection, lack of commissioning, maintenance issues, and wrong fan settings are all associated with inadequate ventilation rates in classrooms (Chan et al., 2020).

Based on a survey of New York State school teachers, there is an association between the classroom's characteristics and building-related health symptoms (Kielb et al., 2015). Classroom's IAQ assessment has been carried out in multiple research studies. Johnson et.al measured CO, CO_2, NO_2, VOC, formaldehyde, particulate matters, temperature, and relative humidity to explore IAQ in 12 Oklahoma City area elementary schools and mentioned the need for additional study to explore the effects of these factors on classroom's IAQ (Johnson et al., 2018). IAQ factors in 64 elementary and middle school classrooms in Michigan were studied to determine ventilation rates, levels of volatile organic compounds (VOCs), bioaerosols, and emission sources. The variability between schools for IAQ variables was less than the variability within schools, which confirms the impact of local emissions, activities, and building features in the quality of air in a school and the need for monitoring of multiple spaces in a school building (Godwin & Batterman, 2007). In a study in the mid-Atlantic region, the indoor concentrations of particulate matters ($PM_{2.5}$), nitrogen dioxide, and carbon monoxide (CO) in 16 public schools in three different seasons were measured. The results of this study suggest the improvement of building conditions to improve indoor air quality in schools (Majd et al., 2019). Appropriate control strategies help to reduce exposure to indoor pollutants (Joana Madureira et al., 2015). The high density of occupants and the sensitivity of children in classrooms may exacerbate IAQ problems in schools. Parents are more worried about schools with observed IAQ problems (Joana Madureira et al., 2015). According to a study in Finland IAQ may be associated with teacher-student relationships. The teacher-student relationship was reported to be worse in schools with IAQ problems compared to the schools with no IAQ problem (Finell et al., 2018). Having a formal IAQ program can engage schools in practices that promote IAQ (Everett Jones et al., 2010) which may result in better performance of students in classrooms. The performance of students is impacted by several internal and external classroom factors. IAQ and thermal comfort conditions of the classroom may influence the performance of students.

There is evidence that IAQ in classrooms may affect a student's health and academic performance (Mendell & Heath, 2005; Shendell et al., 2004a). Previous work on how indoor environmental conditions in K-12 classrooms impact student achievement and health have often focused on only one or two IAQ and TC factors. In the next following sections, IAQ & TC factors in classrooms and the studies which investigate the relationships between these factors and student's academic performance have been reviewed.

2.2.1. Ventilation Rates

The ventilation rate (VR) is a common factor used to describe the IAQ of a space. Several studies around the world have been carried out to measure ventilation rates of schools and discover the association between VRs and student performance (U. Haverinen-Shaughnessy et al., 2011a) and absenteeism (Mendell et al., 2013; Shendell et al., 2004b). Increasing VRs lead to decreasing the concentration of indoor pollutants in classrooms (Rosbach et al., 2016a). Inadequate ventilation is the main reason for higher CO_2 levels in classrooms (Turanjanin et al., 2014). Increasing the ventilation rate in classrooms in the range of 2 L/s.person to 10 L/s.person can lead to significant impacts on student's performance (Wargocki et al., 2020). For classrooms, ASHRAE Standard 62.1 requires the minimum VR for students aged 9+ to be 6.7 L/s·person and for ages 5-8, 7.4 L/s·person (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010). However, according to earlier studies, most of the measured classrooms have VRs below those specified standards (Fisk, 2017). Battermann et al. used a tracer gas method to estimate the VRs in 37 schools and showed the need for additional ventilation in most elementary US school buildings studied (S. Batterman et al., 2017). In England, a study performed with more than 200 students concluded that poor VRs in classrooms significantly impair children's attention and vigilance (Bakó-Biró et al., 2012).

IAQ problems were detected in poorly ventilated classrooms (J. Madureira et al., 2016). Asif et.al measured indoor levels of CO_2 in classrooms of an educational institute and concluded that in buildings with non-centralized systems CO_2 levels exceed from

ASHRAE standard, comparing to buildings with centralized systems (Asif et al., 2018). Gao et al. carried out a study in a Danish elementary school and estimated VRs with peak CO_2 concentration during occupied hours. The VRs ranged between 2-4 L/s·person for classrooms with manually operable windows and around 7.5 L/s·person with mechanical ventilation systems (Gao et al., 2014). Kim et.al conducted a thermal comfort survey among 4866 students in Australia and concluded that students prefer air-conditioning other than fans or windows to provide their comfort (Kim & de Dear, 2018). Mechanical systems are important for classrooms not only for providing satisfactory ventilation rates but for air distribution and contaminant control. Mechanical ventilation can improve occupant's performance and decrease the levels of indoor contaminants (Ben-David et al., 2017). According to a study in 389 Danish schools, students have better performance in schools with balanced mechanical ventilation, comparing to students in schools with natural ventilation (Toftum et al., 2015). Classrooms could have satisfactory ventilation rates but still levels of exposures are still greater than recommended levels (Dorizas et al., 2015). Increasing ventilation rates may reduce CO_2 concentration however, it can increase particle concentration when outdoor air is polluted (Yu et al., 2014). The reduction in ventilation rates due to sustainability and energy consumption may cause classrooms to have a high concentration of CO_2 during occupancy periods (Clements-Croome et al., 2008).

2.2.1.1. Ventilation Rate Estimation

Since VR is often used as an indicator of indoor air quality, the field measurements of VRs in buildings have been conducted for more than 75 years (Persily, 2016). Tracer-gas techniques are commonly used methods to estimate VRs. Building VRs are determined by three main methods: (1) steady-state; (2) decay rate; and (3) build-up (ASTM International, 2019). Choosing the best approach depends on building and system characteristics, time, and resources (Persily, 2016). The use of CO_2 as a tracer gas to estimate VRs is validated by SF_6 measurements (Claude-Alain & Foradini, 2016). For an occupied classroom, using CO_2 emissions from students as a tracer gas has been adopted to calculate VRs (Leclerc et al., 2015; Scheff et al., 2000). VR is a function of the number of people, estimated CO_2 generation rate per occupant, indoor and outdoor air CO_2 concentrations, time intervals of occupancy, and volume of the classroom. There are several studies in which tracer gases were used to determine VRs in classrooms in naturally ventilated schools (Bakó-Biró et al., 2012; Coley & Beisteiner, 2016; Rosbach et al., 2016b) where the decay method is the most used because it is the easiest to set up (Labat et al., 2013). However, in mechanically ventilated schools the most adopted method is steady-state. Table 2 shows an overview of previous studies in mechanically ventilated schools.

Table 2. Previous studies and the method and range of estimated VRs in classrooms with mechanical systems

Number	Authors and Year	Method	Sample Size	Range of VRs (L/s·person)
1	Shendell et al. (2004) (Shendell et al., 2004b)	Steady-State	434	median < 7.5 (max/min unavailable)
2	Haverinen-Shaughnessy et al. (2011) (U. Haverinen-Shaughnessy et al., 2011a)	Steady-State	100	0.90–11.74
3	Taylor et al. 2011 (Wargocki & Wyon, 2007)	Build-up	6	2.7±0.4–9.9±1.6
4	Mendell et al. (2013) (Mendell et al., 2013)	Steady-State	162	2.6–7 (median value)
5	Haverinen-Shaughnessy et al. (2015) (Ulla Haverinen-Shaughnessy et al., 2015)	Steady-State	70	3.6–4.1
6	Batterman et al. (2017) (S. Batterman et al., 2017)	Transient Mass Balance	147	3.81–0.07

2.2.1.1. Ventilation Rate & Academic Performance

Many studies that investigate the relationship between IAQ factors and student's performance, focused on the relationship between a student's performance and ventilation rates. The evidence that there is an association between increased student performance and increased ventilation rates is compelling (Fisk, 2017). Mendell et.al suggested that increasing classroom ventilation rates would decrease illness-related absenteeism (Mendell et al., 2013). Maxwell collected data from 236 NYC middle schools and indicated that there is an association between academic achievement and building conditions (Maxwell, 2016). Table 3 shows the previous literature on the relationship between ventilation and student's performance. Shaughnessy et.al conducted a study in a school district in the USA to investigate the association between the classroom's ventilation rate and student performance (R. J. Shaughnessy et al., 2006). In this study CO_2 concentrations in fifth-grade classrooms in 54 elementary schools in addition to student's reading and math scores were collected. The results of this study mention that there might be a modest association between ventilation rates and math and reading scores. Haverinen-Shaughnessy et.al collected data from 100 fifth grade classrooms and concluded that there might be a linear relationship between classroom ventilation rates and student's academic performance (U. Haverinen-Shaughnessy et al., 2011b). In another study, Haverinen-Shaughnessy et.al conducted a study to collect data from 70 school districts in the Southwestern United States during two academic years. The results of this study show that academic performance has a relationship with classroom ventilation rate and indoor temperature (Ulla Haverinen-Shaughnessy et al., 2015). Toyinbo et.al measured ventilation rates and temperature in 108

Table 3. Previous studies on the relationship between classroom's ventilation rates and student's academic achievement

Author	Type	Year	Variables	Outcomes	Samples	Conclusion
Haverinen-Shaughnessy	Observational	2011	Ventilation	Mathematics, reading scores	100 classrooms	A linear relationship between ventilation rate and test scores for the range of schools with ventilation rates below the recommended minimum.
Bakó-Biró	Experimental	2012	Ventilation	Computerized assessment tests	16 classrooms	Elevated levels of CO_2, due to inadequate ventilation, can affect student's learning
Haverinen-Shaughnessy	Observational	2015	CO_2, and settled dust	Mathematics, reading scores	140 classrooms	Low classroom temperature along with a high ventilation rate could be associated with higher rates of students scoring satisfactory in mathematics and reading tests.
Mendell	Observational	2016	Ventilation	Mathematics, English scores	150 classrooms	A positive association between classroom ventilation rates and learning
Toftum et al.	Observational	2015	Ventilation	Standardized Danish national test	820 classrooms	Higher grades in schools with balanced mechanical ventilation
Toyinbo	Observational	2016	Ventilation rates	Mathematics scores	108 classrooms	Ventilation is associated with thermal comfort and student learning outcomes

elementary classrooms in Finland and concluded that ventilation is associated with thermal comfort and students' learning outcomes (Toyinbo et al., 2016). Mendell et.al analyzed data from 150 classrooms in three California school districts. The results show a potential positive association between classroom ventilation rate and learning (Mendell et al., 2016). Bakó-Biró et.al investigated the effect of classroom ventilation rates on student's performance in 8 primary schools in England. This study shows that elevated levels of CO_2, due to inadequate ventilation, can affect student's learning (Bakó-biró et al., 2012). In a study conducted in Danish schools, it was concluded that students get higher grades in schools with balanced mechanical ventilation or mechanical exhaust compared to students in schools with natural ventilation by manual window opening (Toftum et al., 2015). Reducing CO_2 concentration from 2100 ppm to 900 ppm in classrooms would increase student's performance speed by 12% and decrease student's error rate by 2% (Wargocki et al., 2020).

2.2.2. Temperature

The classroom's thermal environment can affect a student's productivity and performance. Temperature variation in a wide range in classrooms can decrease student's performance (Wargocki & Wyon, 2013). It has been demonstrated that students react faster in doing simple tasks when the classroom's temperature is reduced from elevated levels to a more comfortable range (Bakó-biró et al., 2012). According to a study that links the local daily weather to test scores of 10 million students from high school classes of 2001-2014, hotter days before tests reduce learning. This study found out that "without air conditioning, each 1 ºF increase in school year temperature reduces the amount learned that year by one percent (Goodman et al., 2018). Several previous research suggested the importance of the classroom's thermal condition on the performance of students. In most studies, thermal conditions are characterized by the classroom's temperature. There are multiple studies in the 1960s and 1970s in Europe that studied the effect of temperature on the performance of students. These studies suggested a strong correlation between classroom temperature and student performance (Holmberg & Wyon, 1969; Wyon DP., 1970).

In one of the earliest experiments in the United States in the late 1960s at Kansas State University, students performed school work in a range of 63 to 92 ºF temperatures. Student's had fewer errors at 80 ºF, however, they worked faster at 68 ºF (Pepler & Warner, 1968). In the other experiments in Iowa on 10-12 years old students, Schoer and Shaffran concluded that the performance of students is significantly better in the classroom with lower temperatures in the cooling season (L & Shaffran, 1973). There are few published papers in recent years that investigate the effect of thermal environment and student performance. Table 4 summarized recent studies on the relationship between temperature and student's performance. Wargocki et.al conducted multiple experiments on the relationship between the student's performance and temperature. In an experiment in two classrooms of 10-year students average air temperature reduced from 25 ºC to 20 ºC while outdoor supply increased from 5.2 L/s person to 9.6 L/s person. Mathematics and reading tasks were assigned to students and it was concluded that reduced temperature in summer has a positive impact on students' performance (Wargocki &

Wyon, 2007). A meta-analysis of the published studies on the effects of classroom temperature on student's performance shows the relationship between the classroom's temperature and student's performance. According to this analysis in temperate climates, the performance of psychological tests and school tasks can increase by 20% if the classroom's temperature is reduced from 30 ºC to 20 ºC. In this analysis, 22 ºC is reported as the temperature for optimal performance in classrooms in temperate climates (Wargocki et al., 2019). In another experiment in Denmark 12 subjects were exposed to 23 ºC and 27 ºC while performing typical office work tasks. The results suggest that elevated temperatures may lead to a decrease in performance (Lan et al., 2020). Park investigated the impact of heat stress on exam performance and the educational attainment of New York City high school students. The results of this study show that hot days reduce student's exam scores (J. Park, 2016). In an experiment in tropical regions (with high relative humidity) the performance of schoolwork increase when the temperature reduced from 30 ºC to 25 ºC (Porras-Salazar et al., 2018). In a study in Brazil's hot and humid area perception of students from age 9 to 11 years old about thermal comfort was assessed. Air temperature, mean radiant temperature, humidity, and air velocity in 3 schools and 6 classrooms were recorded. In this study, nearly 50% of students preferred a lower temperature in the classroom (Noda et al., 2020).

Table 4. Previous studies on the relationship between temperature and student's academic achievement

Author (Year)	**Learning Outcomes**	**Grade/ Level**	**Statistical Method**	**Results**
Wargocki and Wyon (2007)	Numerical and language-based tasks	Elementary	A general linear model (GLM)	Reduced temperature in summer has a positive impact on students' performance
Haverinen-Shaughnessy and Shaughnessy (2015)	Math/ reading scores	Elementary	Linear regression analysis	A lower classroom temperature (cooling mode) can be associated with higher mathematics and reading scores
Toyinbo (2016)	Math scores	Elementary	Linear mixed modeling (LMM)	No association between temperature and mathematics scores reported
Park (2016)	Math/ English Language and Arts (ELA) scores	High school	Linear regression analysis	Hot days reduce student's exam scores
Goodman et al. (2018)	Math/ reading scores	High school	Linear regression analysis	Increase school year temperature, decrease learning
Porras-Salazar et al. (2018)	Mathematics/ Reading tasks	Elementary	Wilcoxon Signed-rank Test	Higher performance with the reduction in temperature

In one of the most recent studies in the United States, Haverinen-Shaughnessy et.al used a multilevel approach (Linear mixed models) to investigate the association between temperature and student's test scores in southwestern the United States. In this study, 70 elementary schools (two 5th grade classrooms in each school) were monitored during one academic year. 3109 student's demographic data including gender, ethnicity, lunch-status, English learners, and gifted status were collected in addition to student's mathematics and reading scores. The result of this study suggested a decrease in temperature in the range within 20-25 ºC can increase student's scores (Ulla Haverinen-Shaughnessy & Shaughnessy, 2015). In a study in California schools, many classrooms in the sample were too warm (temperature above 25.6 ºC) to support learning (Chan et al., 2020).

2.2.3. Particulate Matter

Particulate matter is a mixture of solid or liquid particles suspended in the air, which may have different sizes or shapes. Since smaller particles are inhalable they are the main concern of most standards and organizations. According to EPA, particles less than 10 micrometers in diameter can get deep into the lungs (U.S. EPA, 2020c). Fireplaces and tobacco smoke can be the major sources of indoor particles, however, in schools, other factors may impact the concentration of particles in classrooms. School location, classroom occupant density, and ambient PM levels affect classrooms particles concentrations (J. H. Park et al., 2020).

Human activities can lead to a higher concentration of PM_{10} in classrooms (A. Fischer et al., 2015). Measurements of PM_{10} and $PM_{2.5}$ in three primary schools in Portugal show higher levels of coarse particles in classrooms compared to ambient levels. Student's activity highly influences the re-suspension of particles in the classroom's environment which can be deteriorated by inadequate ventilation rates (Almeida et al., 2011). Learning activities are another source of particles in classrooms. According to a study in Poland, educational experiments carried out in classrooms may be an important source of indoor particles (Polednik, 2013). The classroom's flooring type also affects airborne particle levels (R. Shaughnessy & Vu, 2012). In a study conducted by Dorizas et.al in nine primary schools in Greece, indoor to outdoor (I/O) concentration ratios of PM_{10} and $PM_{2.5}$ were greater than one which demonstrates the effect of indoor sources over outdoor air in classroom's particle concentration (Dorizas et al., 2015).

There are studies that have reported the high concentration of particles in classrooms (Wargocki et al., 2008). According to a study in Germany, indoor PM_{10} concentrations in classrooms are 6 times higher than outdoor PM_{10}, and on an equal weight basis, induces more inflammatory and allergenic reactions (Oeder et al., 2012). Higher concentrations of particulate matter can be seen during school hours and effective ventilation can decrease particular matter concentration in classrooms (Boulic et al., 2018). In air-conditioned classrooms, higher air change rates reduce the concentration of particles (Guo et al., 2008). Even though, mechanical ventilation can decrease $PM_{2.5}$ concentration, using low-efficiency filters lead to negative economic impacts (Yuan et al., 2018). Using appropriate filters can reduce the exposure of students to particles in highly polluted areas (van der Zee et al., 2017).

There is evidence that exposure of students to high concentrations of particles is associated with health effects (Alshitawi & Awbi, 2011). There is a limited number of researches on the relationship between student performance and particle concentrations in classrooms. The only study found by the author, which directly studies the impact of particle concentration reduction on student's performance, shows no general effect of the classroom's particle concentration on the student's performance. Wargocki et.al.

conducted an experiment in five elementary public schools (190 students) to determine whether the performance of students in schools is impacted by the reduction of particle concentrations. The results of this study show that the reduction of airborne particles does not have any expected short-term benefit on student's performance (Wargocki et al., 2008). There is research needed to investigate the effects of particles on students (Carrion-Matta et al., 2019).

2.2.4. Total Volatile Organic Compounds (TVOCs)

Total volatile organic compounds (TVOCs) levels have significant weight in the IAQ of a space. Volatile organic compounds (VOCs) are gas phase contaminants emitted from certain products and materials, which may have adverse short-term and long-term health effects. EPA introduced paints, building materials, furnishings, disinfectants, office equipment, etc. as the sources of VOCs in indoor spaces (U.S. EPA, 2020f). High TVOC concentrations, above 1-2 mg/m^3, indicate the presence of strong VOC sources. OSHA and NIOSH have exposure limit standards for VOCs. Indoor levels of VOCs in classrooms are associated with fatigue and headache (Norbäck et al., 2017). According to a study in university classrooms, human occupants were the major contributor to the mass of VOCs (Tang et al., 2016). Carpets in classrooms in classrooms can be a source for VOCs and a causal factor for health symptoms (Daisey et al., 2003). The reduction in the usage of cleaning agents which consist of high VOCs may affect TVOC levels of classrooms (Jamaludin et al., 2016). Materials using in classrooms also have an impact on the concentration of VOCs in classrooms. According to a study in Lawrence Berkeley

National Laboratory wall panel's materials has a small impact on the concentration of several VOCs in classrooms (Hodgson et al., 2002). The classroom's ventilation rate influences the levels of VOCs in classrooms. Inadequate air change rates can increase VOC levels in classrooms (Istrate et al., 2016).

TVOC concentration in the indoor environment may impact the performance of workers in an indoor environment. According to a study on twenty-four participants in New York, worker's exposure to VOCs is associated with lower cognitive scores (J. G. Allen et al., 2016). No study found in which the direct effect of VOCs on student's performance was investigated.

2.2.5. Formaldehyde

Formaldehyde (HCHO) is one of the indoor air pollutants in the classroom, due to its emissions from the materials used in classrooms. Formaldehyde exposure can have negative short-term and long-term health effects and can cause irritation of the skin, eyes, nose, and throat (U.S. EPA, 2020a). According to WHO, four-hour exposure to 0.38 mg/m3 (310 ppb) of formaldehyde is the lowest concentration reported to cause eye irritation. WHO mentions that the range of formaldehyde in schools and kindergartens is between 1.63 ppb to 40.71 ppb. Table 5 shows formaldehyde exposure limits set by different standards.

Table 5. Exposure limits set by different standards

Standard set by	Exposure limit
OSHA PEL	0.75 ppm TWA (750 ppb) 2 PPM STEL (2000 ppb)
ACGIH TLV	0.1 ppm TWA (100 ppb) 0.3 ppm STEL (300 ppb)
MAK (Maximum concentrations at the workplace and biological tolerance for working materials)	0.3 ppm (300 ppb)
WHO (Europe)	81.42 ppb
Canadian standard	0.1 ppm (100 ppb) 0.05 ppm (50 ppb)
NIOSH	16 ppb
ACGIH	300 ppb
OEHHA (California Environmental Protection Agency)	7.3 ppb (8-Hour Inhalation REL)

* Class C (Minimum Acceptable)
*Class B (Acceptable)
*Class A (Aspirational)

A school environment with higher concentrations of formaldehyde may affect the incidence of asthma and sensitivity to furry pets in school (Smedje & Norbäck, 2001), however low concentrations of formaldehyde (< 0.05 ppm) is unlikely to cause acute irritant symptoms (Daisey et al., 2003). According to a two-year study of formaldehyde in seven high schools in central Texas, higher formaldehyde concentration was found at night, when ventilation systems were off (Wade, 2017).

The use of lower-emitting ceiling panels may reduce formaldehyde concentration in classrooms (Hodgson et al., 2002). According to a study in French schools, formaldehyde concentration in classrooms can be reduced significantly, by removing or replacing the main source of emission with a less emissive material and by increasing air change rate in classrooms (Poulhet et al., 2014). In a study in two secondary schools in Croatia, the highest concentration of formaldehyde was observed in a classroom where mold, dampness, and condensation contaminants were visible (Brdarić et al., 2019).

The previous research studies on formaldehyde in indoor environments mostly focused on the assessment of formaldehyde and the potential health effects on occupants. No study was found by the author which investigates the effect of formaldehyde on student's performance.

2.2.6. Ozone

High concentrations of ozone can be harmful to people and the effects can be worse on children. Based on the scientific evidence about the effects of ozone on health, EPA suggests 0.07 ppm as the 8-hour average concentration of ozone in the ground level zone. According to EPA, factors such as temperature, wind speed, and time of the day impact ozone concentrations in indoor environments (U.S. EPA, 2020e). Most indoor ozone concentration originates outdoors, however, because of the large amount of time people spend indoors, indoor ozone exposure is higher than outdoor ozone exposures (Weschler et al., 1989). According to a study in Mexico City, a complex interaction was found between ventilation conditions and outdoor ozone levels in predicting indoor ozone levels (G. Allen et al., 1996).

Office activities, such as printing and photocopying affect indoor ozone concentration in classrooms (Othman et al., 2020). To reduce ozone concentrations in schools, it is recommended to reduce the penetration of outdoor ozone by filtering ozone from the supply air, limit the use of printers and photocopiers indoors and limit the use of materials and products the emissions of which react with ozone (Salonen et al., 2018). In a study in Sweden, indoor ozone concentration in a classroom was measured with and without occupants to investigate the effects of occupants on indoor ozone concentrations. The results of this study show that ozone removal by occupants was approximately 2.6 times larger than the surfaces and furniture that exist in classrooms (Andreas Fischer et al., 2013). In another study in two primary schools in Turkey, ozone was found to be higher for the students living in the sub-urban area comparing to those living in the urban area (Demirel et al., 2014).

The previous literature on Ozone at schools is mostly related to outdoor ozone measurements at schools and student’s health. In a study conducted in Southern California which investigates the effects of outdoor ozone concentration on student’s performance, the results have not reported outdoor ozone as a significant factor in student’s academic performance (Zweig et al., 2009).

2.2.7. Nitrogen Dioxide

Nitrogen dioxide (NO_2), is one of the air pollutants which can have indoor or outdoor sources. The main sources of NO_2 are combustion processes and tobacco smoke (U.S. EPA, 2020d). High exposure to NO_2 may increase asthma symptoms in students (Chauhan et al., 2003). Low-level NO_2 exposure may increase the risk of respiratory infections in children (U.S. EPA, 2020d). ASHRAE and EPA suggested 0.053 ppm as the average 24-hour limit for NO_2 in outdoor air. WHO defines 40 $\mu g/m^3$ as the annual mean concentration for NO_2. School's location and outdoor NO_2 concentration have an impact on student's exposure to NO_2 (Rijnders et al., 2001). Road traffic and school powerplants affect the classroom's indoor NO_2 concentrations (Brdarić et al., 2019).

Even though NO_2 is one of the most common air pollutants and there scientific research studies on its adverse effects on human health, there are limited studies on the exposure to NO_2 in different indoor environments and its effects on occupant's health and performance. In a study in China, nitrogen dioxide concentration was measured in 30 classrooms to investigate the effects of NO_2 and asthma symptoms. The results of this study mentioned that indoor NO_2 concentration is associated with asthma symptoms in students (Mi et al., 2006). According to Salonen et.al the calculated mean and median concentration of NO_2 in school is 29.4 $\mu g/m^3$ and 21.1 $\mu g/m^3$ respectively (Salonen et al., 2019). Zweig et.al conducted a study to investigate the relationship between outdoor air pollution levels and standardized state test scores of California public school children. In this study outdoor air pollution data and family background information have been used.

This study found that a 10% decrease in outdoor NO_2 concentration, may raise math scores by 0.18% (Jacqueline S. Zweig et al., 2009).

2.2.8. Carbon Monoxide

Carbon monoxide is an odorless, colorless gas even at low concentrations may have health issues for human beings. Tobacco smoke and combustions are the main sources of CO. According to the Occupational Safety and Health Administration (OSHA), the permissible exposure limit (PEL) for carbon monoxide is 50 ppm. In schools, the main source of CO is outdoors and in classrooms, CO levels are expected to be lower than outdoor levels. In a study in Korea, higher CO levels were observed in newly constructed schools (Pegas et al., 2011). According to a study in 14 elementary schools in Portugal, CO levels ranged from less than 1 mg/m^3 to 12.5 mg/m^3 (Pegas et al., 2011). Indoor CO levels in classrooms are mostly influenced by outdoor CO levels, however, some indoor learning activities such as experiments that include combustion may increase CO levels in classrooms.Previous literature studies on CO in classrooms mostly focused on the measurement and assessment of CO levels in classrooms. Based on the author's knowledge, no study has tried to investigate the effects of CO on student's performance.

2.3. Academic achievement and demographic

Academic achievement or academic performance is referred to as the student's long-term or short-term goals. Increasing efficiency and student achievement can reduce the college cost of remediation by $3.6 billion annually (U.S. Department of Education). There is a variety of factors that contribute to student's academic achievements. Achievement gaps developed in a diverse racial environment (Bali & Alvarez, 2004). In 1966, Coleman published his study on "Equality of Educational Opportunity" in which the influence of student's socioeconomic background was introduced as a strong predictor of student achievement (Thomas & Stockton, 2003). Coleman's study was a landmark in student achievement studies which drew the researcher's attention to a variety of social factors in student's academic achievement.

Federal, state, and local education policymakers are seeking to close the gap between advantaged students and disadvantaged students. School quality and the school's access to the resources are some of the factors that affect student's performance (Eide & Showalter, 1998; Wößmann, 2003). Other than school-related factors students' family-related factors are also important in the success of students. Parent involvement according to race and socioeconomic condition of the family may promote student's achievement (Desimone, 1999). There is evidence that demographic data which are consist of specific information about gender, socioeconomic background, and race may have associations with the performance of students at schools.

The eligibility of students for a free lunch is being used in education research as an indicator of student's socioeconomic status. Students in the United States whose household income is less than 130% of the poverty line are eligible for free lunch, and students with household income between 130% and 185% of the poverty line qualify for reduced-price lunch at schools. According to a predictive validity analysis study in a limited number of districts in California and Oregon, lunch status predicts academic achievement more than IRS-reported income (Hakuta et al., 2000). However, it should be noted that the lunch status of a student is not a comprehensive measure for the socioeconomic background of students (Harwell & LeBeau, 2010).

The level of student's English language skills can be another factor that may have associations with the students' scores. Studies can design in which students are grouped based on their proficiency in the English language (Shaftel et al., 2006). Comparing to native English spoken students, English learner students should expose to more instruction to improve their language scores (Callahan, 2005). Depending on the previous educational experience and the exposure to the English language, English learner students may display a different range of English language proficiency (Shaftel et al., 2006). According to a study in California, a widening academic performance gap between English learner students and native speakers exists (Hakuta et al., 2000).

There are several studies in which the associations between gender, socioeconomic background, and student achievement have been discussed. Petty et.al performed a study in North Carolina on 64980 students from 358 schools in grades 9-12 to explore factors that might have an impact on math achievement. The results of this study show a statistically significant difference for ethnicity, socioeconomic status, and parental education levels however, no gender effects were found statistically significant (Petty et al., 2013). Hyde et.al conducted a study on grades 2 to 11 students and concluded that the general population no longer shows a gender difference in math skills, although there is evidence of greater male variability in scores (Hyde et al., 2008). Quinn et.al used a sample of 21409 students from 1000 schools and observed student's science scores from grades 3 to 8. They found that the Black-White science test score gap remains stable in these years however, the Hispanic-White narrows and the Asian-White gap closes by grade 8 (Quinn & Cooc, 2015).

2.4. Conclusion and future research

Even though ventilation rates are important for measuring IAQ, limited studies have been done to determine the best method to estimate VRs. In most of the previous literature, one method is used to estimate VRs, however, the estimates may not be independent of the adopted method. Since there are systematic and random errors in any measurements, some uncertainty in the measured values may be due to the measurement procedure, the skill of the operators, and the environment (ISO, 2010). Moreover, the selected individual approach has uncertainties and will be influenced by the activity levels of the occupants (i.e. CO_2 generation rate). To the best of the authors' knowledge, no research compares the uncertainty analysis (error propagation) for these different methods of ventilation estimation. In order to fill this knowledge gap, the research team performed a novel uncertainty analysis by comparing three typical tracer-gas methods used to calculate ventilation rates based on measured CO_2-levels. Uncertainty analysis was carried out to compare these methods with the consideration of each variable's accuracy and errors. The factor that contributes to the largest portion of uncertainty was also identified.

The majority of prior studies on the relationship between students' performance and classrooms' environmental factors focused on a specific variable (e.g. ventilation rate or temperature) independently of other IAQ and TC factors. Most studies focused on elementary schools and there is a lack of studies for middle and high-school students. In the previous studies on the relationship between IAQ, TC, and students' performance, only CO_2 concentrations and/or ventilation rates were chosen as the indicators of IAQ and the air temperature was the only measured factor that indicates classrooms' thermal environment. In this study, more comprehensive measurements of IAQ and TC factors in a relatively large sample size within different school districts have been carried out. Annually repeated measurements in three seasons helped to analyze the seasonal associations between IAQ, TC factors, and student scores. Most previous literature also did not consider the effects of student socio-economic status on performance. Based on the authors' knowledge, there are a limited number of studies that focus on the relationships between a broader range of IAQ factors and demographic interactions, and academic performance. To the best of the authors' knowledge, prior studies use classroom aggregated data (e.g. percentage of free-reduced lunch, percentage of English Language learners, percentage of mathematics scores in the classroom) to analyze the associations between classrooms' IAQ, TC, and students scores. To fill these gaps This study uses student-level data to investigates the classrooms' major IAQ, TC factors, and interactions with demographics, high performers, and low-performs with student academic performance. The results of this study can be utilized by school districts or researchers to design experimental studies which are focused on the relationship between classrooms' indoor environmental factors and student's performance.

Chapter 3. Methodology

3.1. Classroom's data

Measurements of indoor air and thermal environmental quality have been made in 220 classrooms within 39 schools in the Midwest region of the United States from 2015-2017. 144 elementary classrooms, 32 middle school classrooms, and 44 high school classrooms in five school districts were selected. The classrooms include 3rd, 5th, 8^{th,} and 11th-grade levels. These garde levels have state standardized tests. Multiple classrooms from each school were chosen for environmental sampling. In total, 74 grade three classrooms, 70 grade five classrooms, 32 grade eight classrooms, and 40 grade eleven classrooms were selected (Figure 1). Students in elementary school classrooms (grade 3 & 5) spend all day in one classroom, while students in middle school (grade 8) and high school (grade 11) spend the day in multiple classrooms. Figure 2 shows samples of measured classrooms. In this study, elementary school students are analyzed in one group and middle school and high school students are analyzed together in a separate group.

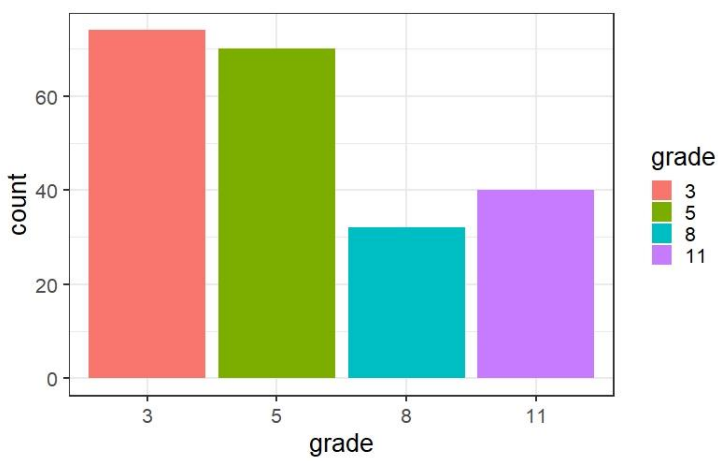


Figure 1. Number of classrooms in each grade in the sample

Figure 2. Sample of measured classrooms

Classrooms have acoustical ceiling panels for the ceiling. A combination of carpet and hard floor or 100% carpet were used for the floors (table 6). In each school visit the volume and occupancy of each classroom were recorded. The volume of studied classrooms is between 100 and 330 m^3.

Table 6. classrooms' flooring and ceiling materials

		Number of classrooms
Ceiling	Acoustical ceiling panels	212
	Drywall ceiling	8
Flooring	Carpet	147
	Combination of carpet and hard floor	73

NIOSH dampness and mold assessment checklist were used to identify the dampness and mold in classrooms. The research team, in seasonal visits, looked for any sign of damage, mold, or dampness on the surface of classrooms' walls, ceilings, and floors. According to

NIOSH, the damage could include rust, peeling paint, and deteriorated building materials. The stain could include discoloration due to possible water leaks. Mold could include spots colored differently than the underlying material and damp could include visible signs of moisture.

All measured classrooms were mechanically ventilated. Heat pumps, unit ventilators, and centralized systems with variable air volume (VAV) or air handling units (AHU) are the three main air side systems that serve classrooms. In total, there were 177 classrooms with single-zone systems including heat pumps with dedicated outdoor air system (DOAS) or energy recovery ventilation (ERV) and unit ventilators attached to an external wall for fresh air. There were 43 classrooms with multi-zone centralized systems with VAV or AHU. Table 7 shows the number of classrooms with each system in classrooms.

Table 7. The number of mechanical systems in classrooms

Mechanical System	Number of classrooms
Single zone	177
Multizone	43

3.2. Classroom Environmental Data Sampling

The measurements of classrooms' indoor air quality and thermal conditions took place in both occupied and unoccupied conditions. The occupied data were logged continuously over 36 hours during two consecutive school days. These two-day measurements were repeated three times in each classroom, roughly corresponding to once in the fall, winter, and spring seasons. The measurements and subsequent calculations for IAQ & thermal comfort variables were explained in the next section. Appendix D shows the distribution of the measured variables. The measurement procedures and basic descriptive results are explained in greater detail in papers (Deng & Lau, 2019; Kabirikopaei et al., 2019).

3.2.1 Indoor Air Quality (IAQ) & Thermal Comfort

IAQ occupied measurements taken place during two school days and the data were logged continuously over 36 hours. Occupied measurements consist of carbon dioxide (CO_2), formaldehyde, fine particles (0.3– 2.5 micron), and coarse particles (2.5- 10 micron). Due to the limited budget, unoccupied measurements were taken place in a short timeframe after students' dismissal. Unoccupied measurements include air velocity, Carbon monoxide (CO), nitrogen dioxide, ozone (O_3), Total volatile organic compounds (TVOC).

To measure CO_2 concentration levels, four TelairE (model 7001) CO_2 sensors were placed for each classroom near the supply air diffuser, the return air grill, the teacher's desk, and one outdoors (Figure 3). Each sensor was calibrated in-house over two weeks with nitrogen as the zero CO_2 concentration (recommended by the manufacturer). According to the manufacturer, sensor accuracy is ±50 ppm or 5% of the reading, which is the range of uncertainty for CO_2 readings. The limit of detection for the CO_2 sensor attached to the data logger is 2500 ppm, however, the CO_2 sensor's limit of detection alone is higher. Each week 20 sensors measured five classrooms.

Figure 3. CO_2 sensor deployed near supply diffusers

A particle counter and formaldehyde monitor were used in the wire box near the teacher's desk. The particle counter recorded the size distribution of particles with aerodynamic diameter from 0.3 μm to 10 μm. Two door-state loggers were also used to record the door status (the proportion of the door opened or closed). Indoor dry bulb temperature and relative humidity were measured by four Hobo loggers attached to CO_2 meters. Globe temperature was measured by a black globe temperature.

The unoccupied measurement of IAQ determines the gas-phase contaminants concentrations. Due to the resource constraints, pollutants that are usually not generated indoor and the IAQ factors measured from expensive equipment were measured during the unoccupied time only for a 10-15 minute timeframe in each season. Carbon monoxide, nitrogen dioxide, and ozone were measured after classes for a limited time (around 15 minutes). Total volatile organic compounds (TVOC) were also measured by an indoor air probe. NIOSH dampness and mold assessment sheets were employed to determine if there is any sign of mold that could be found in classrooms visually. Air velocity in different heights was also measured in unoccupied time by placing the equipment in the middle of the classroom while the HVAC systems are on.

3.3. Student Data

Students' mathematics and reading scores for those attending studied classrooms were collected. Standard scores were converted to percentile rank for each student based on the state's conversion guide. After removing students with missing data from the sample, finally, 1468 elementary students and 1239 unique middle and high school students were used for the analysis. Figures 4 and 5 show the range of reading and mathematics scores for elementary school students and middle-high school students, respectively.

Figure 4. The range of mathematics and reading scores (percentile rank) for elementary school students

Demographic data were used to group students. Demographic data include gender, ethnicity (white/ not white), lunch-pay status (free, reduced, or full-price school lunch), and English language learners. Table 8 shows a summary of the number of each demographic group in elementary schools and middle-high schools.

Figure 5. The range of mathematics and reading scores (percentile rank) for middle-high school students

Figure 6 shows the number of male and female students in elementary school classrooms and middle-high school classrooms (grouped by grade). In total, there are 738 male students and 730 female students in elementary schools. There are 627 male students and 612 female students exist in middle-high school schools.

Table 8. summary of demographic groups in elementary schools and middle-high schools

	Elementary schools	**Middle schools & High schools**
Total number of students	1468	1239
Free-reduced lunch students	682	545
Not white students	239	228
English language learners	108	94
male	738	627
female	730	612

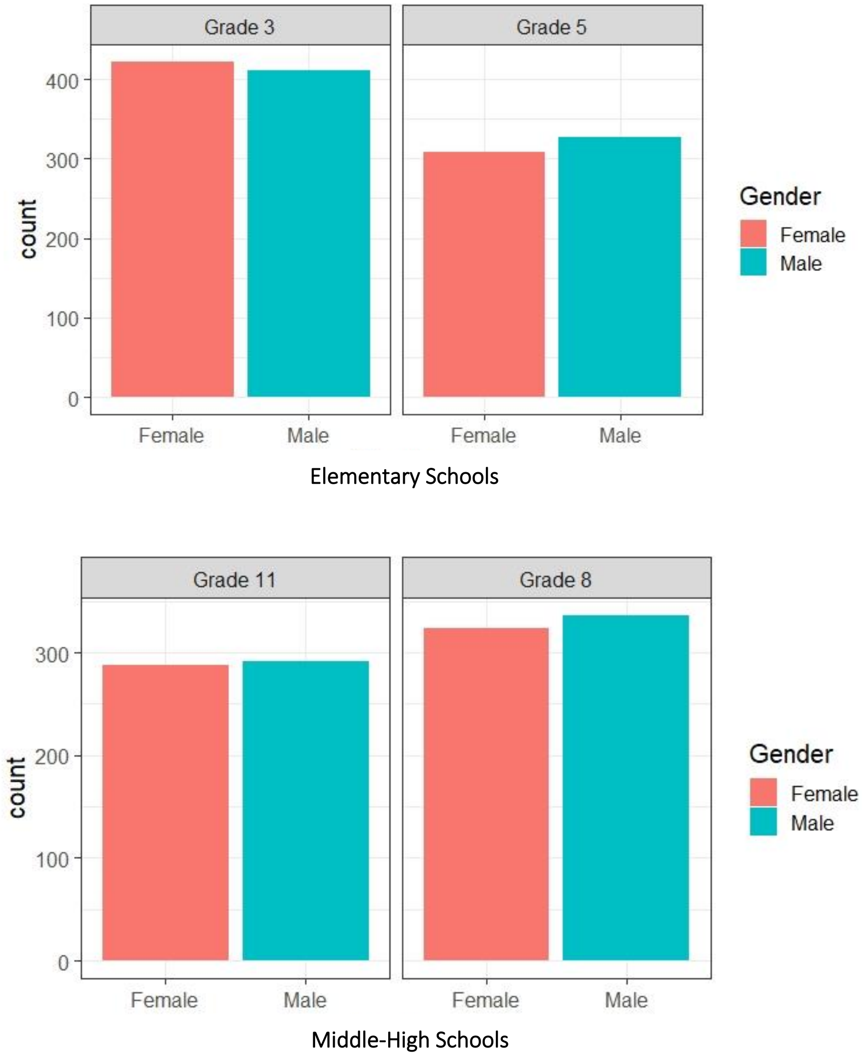
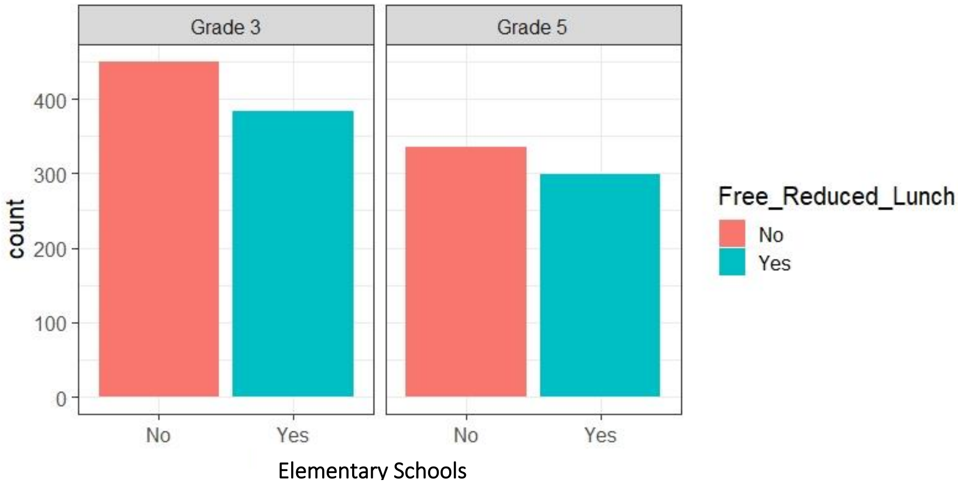


Figure 6. Number of male and female students in elementary and middle-high school classrooms (grouped by grade)

Figure 7 shows the number of free-reduced lunch students in each grade in elementary schools and middle-high schools. In this study, free lunch students and reduced-price lunch students were grouped together (free-reduced lunch). In total, there are 682 free-reduced lunch students in elementary schools (out of 1468 students) and 545 free-reduced lunch students in middle-high schools (out of 1239 students).



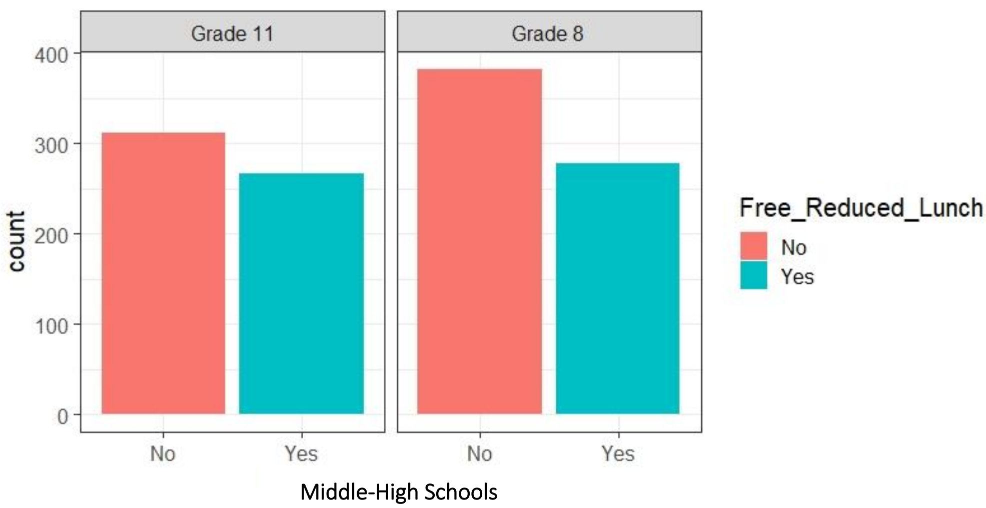


Figure 7. Number of free-reduced lunch students in elementary and middle-high school classrooms (grouped by grade)

Figure 8 shows the number of English language learners in each grade in elementary schools and middle-high schools. In total, there are 108 English language learner students in elementary schools and 94 English language learner students in middle-high schools.

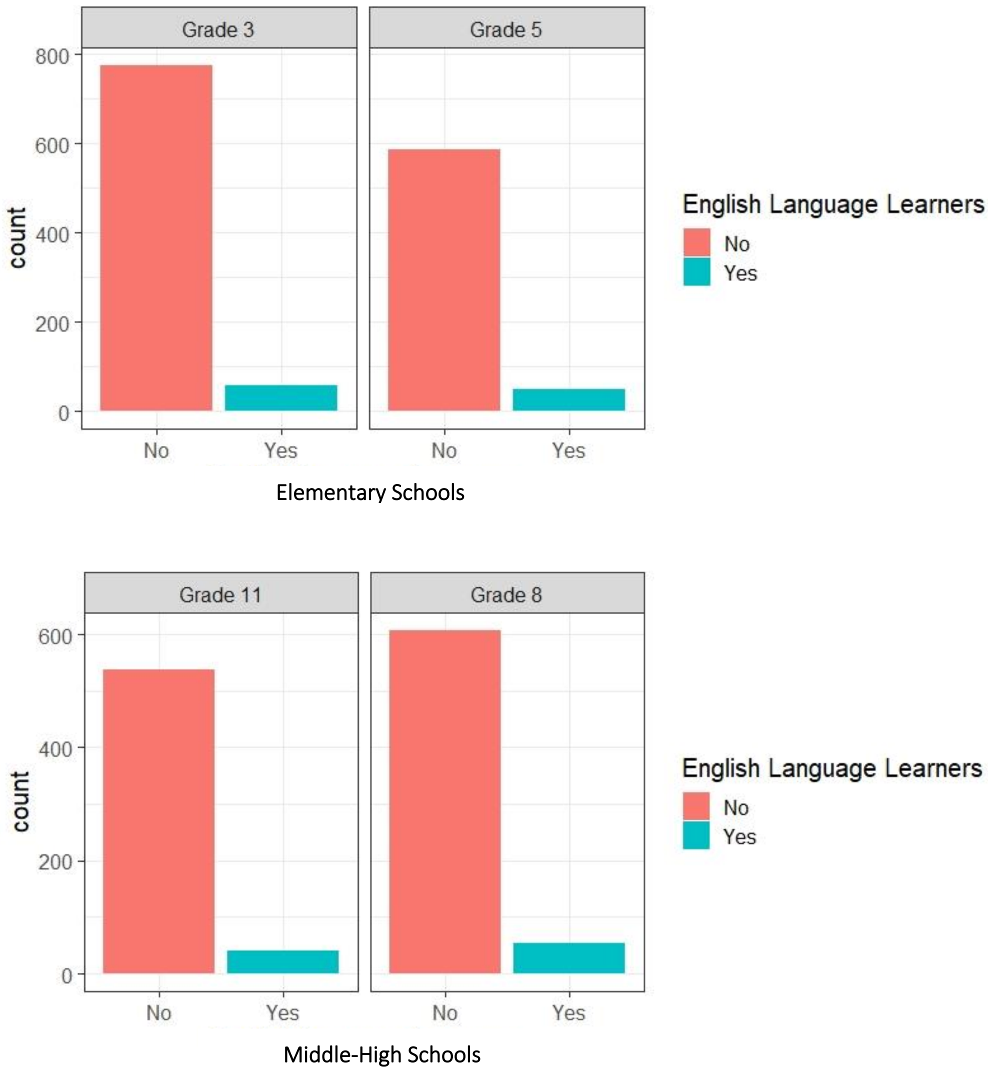


Figure 8. Number of English language learners in elementary and middle-high school classrooms (grouped by grade)

Figure 9 shows the number of white & not-white students in each grade in elementary schools and middle-high schools. In this study, all minority groups (American Indian or Alaskan Native, Asian- Pacific Islander, Black, and Hispanic) students grouped together as “not-white” students. In total, there are 239 not-white students in elementary schools and 228 not-white students in middle-high schools.

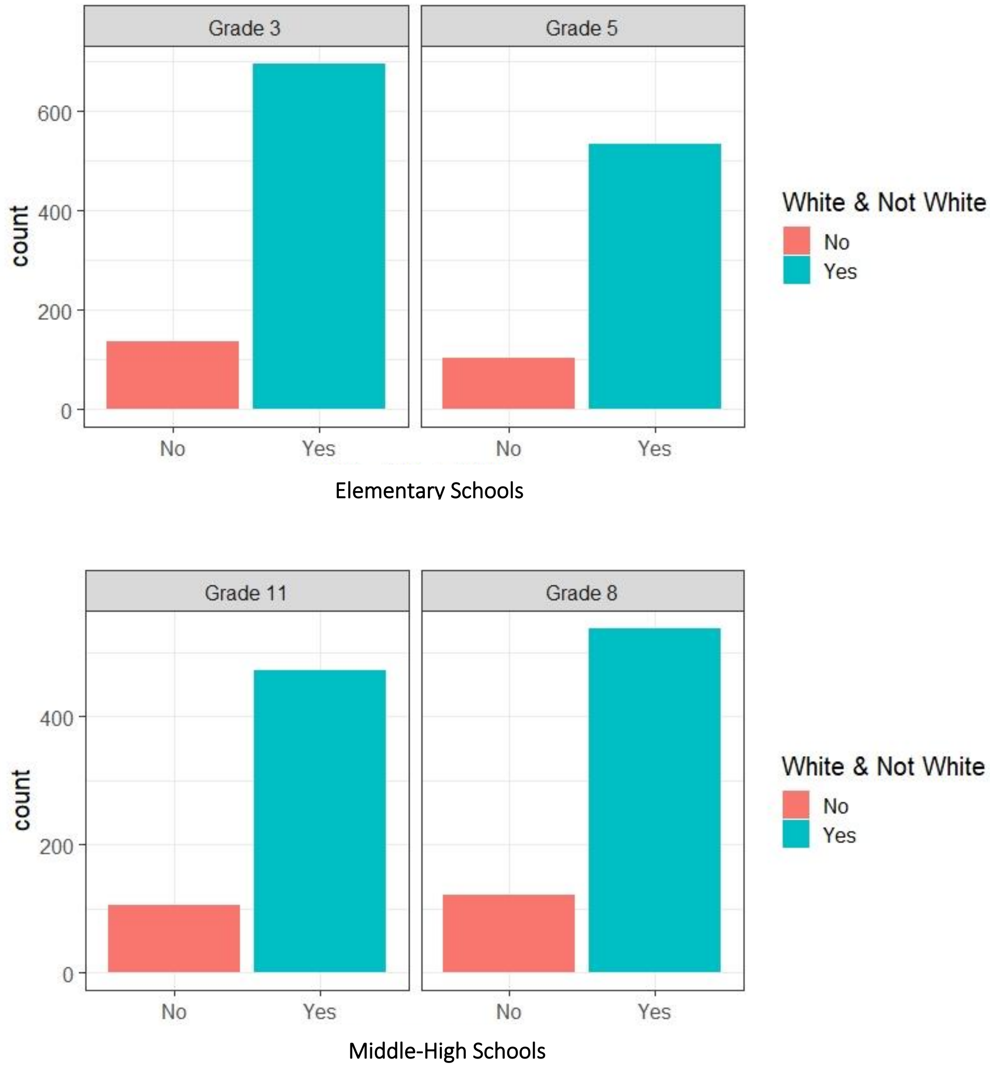


Figure 9. Number of white & not-white students in elementary and middle-high school classrooms (grouped by grade)

3.4. Data Cleaning

Except for formaldehyde, the average of the logged data during occupied hours was used for the analysis. For formaldehyde, maximum concentration during occupied hours was used for the fall season while data for winter and spring were removed due to readings with low concentrations (<10 ppb). Occupied time frames were selected based on schools' start time and end time. Classrooms were classified into two groups regarding ventilation systems: 1) multi-zone (classrooms with centralized systems with Variable Air Volume (VAV) and recirculation pathways), 2) single-zone (classrooms with heat pumps with dedicated outdoor air systems or classrooms with unit ventilators). Therefore, a categorical variable describes the difference between mechanical systems in classrooms: multizone versus single-zone.

The ninety-fifth percentile of the 5-min moving average of indoor CO_2 values in occupied hours in each day was picked as the steady-state concentration. If more than 20% of the data were reported missing from a sensor, the remaining data from that sensor were eliminated for the final analysis, and the remaining sensors in the classroom were used to obtain CO_2 concentration. The VRs for each classroom in each of the three seasons were estimated using three different methods and the uncertainty analysis was performed for all calculated VRs. Due to a lower uncertainty, to determine ventilation rates, the steady-state (constant concentration) method was used. The ventilation rate estimation process and uncertainty analysis are explained in detail in section 3.5.

3.5. Research Question 1 (ventilation rate estimations)

The following research question (research question 1) is addresses in this section: "How different the ventilation rate estimations based on various CO_2-based methods? Which method has the least uncertainty for estimating ventilation rates in classrooms?".

In order to estimate VRs, a single tracer gas approach is often used (Persily, 2016). In the occupied schools, CO_2 generation from the students was used as a tracer gas to evaluate the ventilation quality. The decay, build-up (constant injection), and steady-state (constant concentration) methods used are described in ASTM E741 (ASTM International, 2019) and discussed in detail below.

3.5.1. Steady-state

The peak CO_2 approach is a single-zone steady-state tracer technique requiring the following assumptions: occupant CO_2 generation rate and outdoor air CO_2 concentration should be known and assumed to be constant during the occupancy period. Since this method is a single zone method, it can be only used to estimate ventilation rate in a building with a uniform CO_2 concentration (Persily, 2016). According to Persily, the time required to achieve a steady-state depends on the air change of the building. For a given air change rate, the concentration will be within 95% of steady-state after three time-constants, where the time-constant is the inverse of the air change rate (Persily, 1997). In the studied classrooms in this research, since the cumulative occupied hours are between 6-8 hours, the research team assumed that the classrooms reached a steady-state during the occupied time and when the number of students, the ventilation rate, and the outdoor CO_2 concentration were constant. In this study, 95^{th} percentile of the 5-min moving average of indoor CO_2 values in occupied hours in each day was used as the steady-state concentration (Mendell et al., 2013). Figure 10 shows a steady-state method with 95^{th} percentile of the CO_2 concentration used to estimate ventilation rate.

Equation (1) is used in this method(ASTM International, 2018):

$$Q_{Steady-State} = \frac{10^6\ G}{C_{steady-state} - C_{outdoor}} \tag{1}$$

where Q is the ventilation rate of the space (L/s), G is the CO_2 generation rate in the zone (L/s), $C_{steady-state}$ is the steady-state CO_2 concentration in the zone (ppm), and $C_{outdoor}$ = outdoor CO_2 concentration.

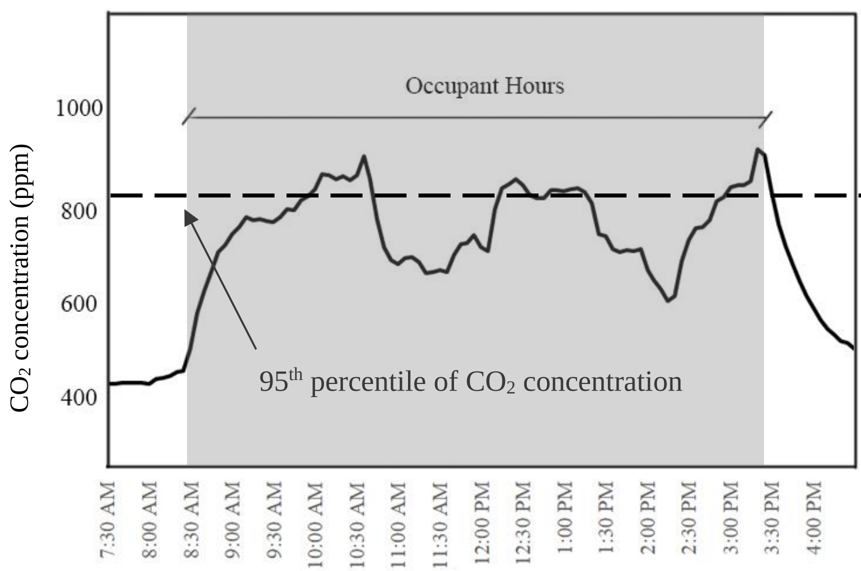


Figure 10. Steady-state method VR estimation for a particular classroom in this study

3.5.2. Decay

According to ASTM E741, the decay rate is one of the methods to determine the average ventilation rate in space. By injecting a tracer gas and measuring the rate of the reduction of the gas concentration over a certain period, decay rate can be used to determine the ventilation rate of space. In this study, CO_2 generation from the occupants is used as the injected tracer gas measuring the decay of the gas beginning at the dismissal of the occupants. The average VR, during the occupants' dismissal period, is calculated by the difference between the logarithms of the initial and final CO_2 concentration and dividing that by the time period (ASTM International, 2019). In this study, the research team assumed the VR is constant during this time period since in most cases the ventilation systems continued to operate after the students left the classrooms. The school's dismissal time was used as the start of the decay rate and a one-hour was selected as the time period (Figure 11). Equation 2 was used to estimate VR for the decay rate method (Stuart Batterman, 2017):

$$Q_{Decay} = \frac{V}{\Delta t} \ln \frac{(C_1 - C_{outdoor})}{(C_0 - C_{outdoor})} \qquad (2)$$

where Q is the estimated ventilation rate (L/s), V is the volume of the space (m^3), C_1 is the maximum CO_2 concentration in the decay period, C_0 is the minimum CO_2 concentration in decay period, $C_{outdoor}$ is outdoor CO_2 concentration and Δt is time period (hour).

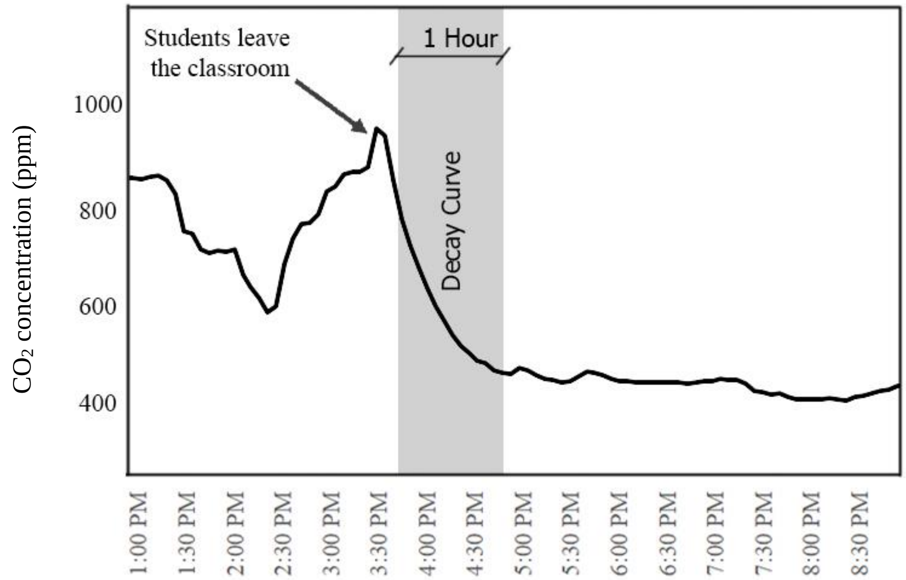


Figure 11. Decay method VR estimation for a particular classroom

3.5.3. Build-up

The build-up method (also known as the constant injection tracer approach) used different CO_2 observations during the measurement period. This method assumes the air change rate and CO_2 generation rate are constant during the study (Stuart Batterman, 2017). Also assumed is that the schools in this study are airtight since they are designed to be served by mechanical systems, however doors opening can affect the rate of VR. In all cases, the research team used a build-up period of one hour beginning when the students enter (Figure 12).

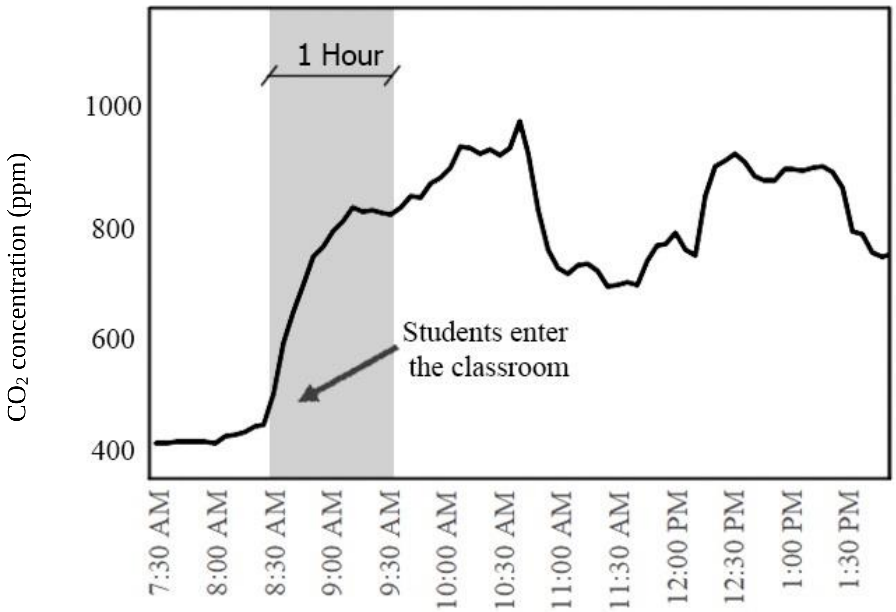


Figure 12. Build-up method VR estimation for a particular classroom

Equation (3) is used to estimate the ventilation rate for the build-up method [16,28]:

$$Q_{Build-up} = 6 \times 10^4 \, n \, G_p \frac{\sum_{t=1}^{12}\left(\frac{1}{C_t - C_{outdoor}}\right)}{12} - \frac{V}{\Delta t} \ln \frac{(C_1 - C_{outdoor})}{(C_0 - C_{outdoor})} \qquad (3)$$

where Q is estimated ventilation rate (L/s), C_t is CO_2 concentration at each time step, C_1 is maximum CO_2 concentration during the build-up period, C_0 is minimum CO_2 concentration during the build-up period, $C_{outdoor}$ is outdoor CO_2 concentration, Δt is time period (hour), V is the volume of the space (m^3), n is the number of the occupants in the space, and G_p is the CO_2 generation rate (L/s·person).

3.5.4. CO2 generation rate

People emit CO_2 at a rate based on their age and level of activity. The monitoring of carbon dioxide concentration is commonly used in estimating ventilation rate for several reasons: (1) people are likely to be the only generating source of CO_2 indoors, (2) indoor CO_2 concentrations are often above the outdoor concentration (Persily, 1997), (3) it is low-cost since CO_2 sensors are readily available, and (4) CO_2 sensors demonstrate acceptable accuracy.

Total CO_2 generation rate (L/min) for the classrooms was estimated based on the number of students present, their activity levels, age group, and gender (ASTM International, 2018; Stuart Batterman, 2017). Equal numbers of girls and boys were assumed in the measured classrooms since the actual gender ratio was not recorded, thus all the above factors may lead to uncertainty for the CO_2 generation rate.

Table 9 shows the CO_2 emissions based on the age range and identifies the number of classrooms with that age range. The CO_2 generation rate differential and range are also shown (ranging from 100% girls to 100% boys).

Table 9. CO_2 generation rate adopted in this study per age range

Age range	**Number of classrooms**	**CO_2 generation rate- L/min (equal gender)**	**Rate differential (all girls-all boys)**
8-9	74	0.208	0.001 (0.208-0.209)
10-11	70	0.244	0.004 (0.242-0.246)
13-14	32	0.303	0.009 (0.308-0.299)
16-17	44	0.337	0.040 (0.357-0.317)

3.5.5 Uncertainty analysis (error propagation)

According to the Guide to the Expression of Uncertainty in Measurement (GUM), systematic error is defined as “the difference between the offset value and true quantity value,” while a random error is associated with the differences among the multiple measurements. According to ISO (International Organization for Standardization) and IEC (the International Electrotechnical Commission) Measurement uncertainty is defined as a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used” (ISO, 2010).

Ventilation rate is a function of the number of people, estimated CO_2 generation rate per occupant, indoor and outdoor CO_2 concentrations, time intervals of occupancy, and volume of the classroom. In the uncertainty analysis, we investigated how the errors in measurements propagated to the estimated ventilation rates. Equation (4) was used to calculate uncertainty:

$$E = \sqrt{\sum_{i=1}^{N} \left(\Delta u_i \; \frac{\partial f}{\partial u_i}\right)^2} \tag{4}$$

where the derivative terms $\left(\Delta u_i \; \frac{\partial f}{\partial u_i}\right)$ are describing the sensitivity of ventilation rates to the changes in the variable, and the value of error (E) is associated with the reflection of individual uncertainties as they are propagated through final results (Figliola & Beasley, 2006).

In the steady-state method, the number of students, CO_2 generation rates, steady-state CO_2 concentration, and outdoor CO_2 concentration are measured values. In the decay method, classroom volume and CO_2 concentration are measured values. In the build-up method, CO_2 concentrations, the volume of the classrooms, number of students and CO_2 generation rate are the measured values (Table 10).

The error (Δu_i in equation 4) for CO_2 measurements are considered based on manufacturers accuracy for CO_2 sensors, therefore 50ppm is used as the error for CO_2 concentrations. To calculate the CO_2 generation rate, it was assumed that the number of girls and boys are equal in the classrooms, then the CO_2 generation rate of all-boys was used as the upper bound and the CO_2 generation rate of all-girls was used as the lower bound for the uncertainty range. The area of classrooms was calculated based on multiplying the length and width of each room. However, some rooms have non-rectangle and irregular shapes in the floor plan (such as additional spaces for beams/ columns), 10% was assumed as the error of the volume in measurements.

Table 10. Measured variables used in the estimation of VR for each method

Method	**Number of students**	**CO_2 generation rates**	**Steady-state CO_2 concentration**	**Outdoor CO_2 concentration**	**Classroom volume**
Steady-state	x	x	x	x	
Decay			x	x	x
Build-up	x	x	x	x	x

3.6. Research Question 2

The following research question (research question 2) is addresses in this section: "Do indoor air quality, thermal environmental factors vary on the classroom level or the variations are limited to the school level?"

3.6.1. Analysis of variance (ANOVA)

To investigate the variation of each variable among classrooms of a school, a one-way analysis of variance (ANOVA) is used. The one-way ANOVA determines if there is any statistically significant difference between the means of variables measured at the classroom level in each school. The Anova analysis is carried out in R by using "aov" function from package "stats".

3.7. Feature selection

Since the classroom environmental data were collected in three seasons (Fall, Winter, and Spring) and there were observable seasonal variations, a correlation study, and Omnibus test was conducted to help to justify the decision of averaging these seasonal data and feature selection.

In the correlation study as an exploratory analysis, the linearity between seasonal data for each variable is examined. If the p-value of the resulting test statistic is smaller than the significance level (0.05), the null hypothesis will be rejected in favor of the alternative. When the null hypothesis is rejected it will be concluded that there is sufficient evidence at the significance level that there is a linear relationship between seasonal data. R programming and Pearson correlation method are used to explore the linearity between seasonal data.

The omnibus test is similar to linear regression with each variable for three seasons as the independent inputs, while student's math and reading scores as the dependent output ($Y = a_1*X_f + a_2*X_w + a_3*X_s + error$). The Null Hypothesis is $a_1=a_2=a_3$. If the coefficients of the variable are statistically significantly different to others (with P-value <0.05), the Null hypothesis was rejected and that variable was kept in three seasons as three separate input variables otherwise seasonal data were merged into one input variable by averaging the data from three seasons. In this study the results of the omnibus test on the seasonal data from Kabirilkopaei et al., 2021 were used.

3.8. Research Question 3

What are the associations between indoor air quality, thermal environmental factors, and student's academic achievement in different demographic groups?

- Do high-performing and low-performing students respond to IAQ, thermal similarly?
- Do students in different demographic groups respond differently to IAQ, thermal factors?

3.8.1. Hierarchical linear modeling (HLM)

Statistical methods are widey used in different fields of engineering (Almaghrebi et al., 2020; Ebrahimifakhar et al., 2020). Hierarchical linear modeling (HLM) was used to analyze the data. HLM is also called multi-level modeling and is a complex form of ordinary least squares (OLS) regression. This method can be used when the predictor variables are at varying hierarchical levels, and HLM analyzes the variance in the outcome variables (Woltman et al., 2012). In this study, the dataset had two levels of data. Mathematics scores, reading scores, and individual demographic data were considered student-level, while IAQ and TC data were considered classroom-level. Therefore, student-level data are nested within classroom-level data. HLM can identify the relationship between classroom-level conditions and academics by taking both student-level and classroom-level regression relationships into account. R programming with the lme4 package was used to analyze the data. This package uses maximum likelihood (ML) or restricted maximum likelihood (REML) to estimate parameters in a multi-level model (Bates et al., 2015). The ML method was adopted for this analysis.

In the hierarchical model, a separate level-one model (student-level) is developed for each level-two (classroom or school level) unit. The model takes the form of a simple regression (equation 4) developed for each student:

$$Y_{ij} = \beta_{0j} + \beta_{1j}X_{ij} + r_{ij} \tag{4}$$

Where $Y_{ij} =$ Mathematics or reading score for student i in classroom j, $X_{ij} =$ demographic data (lunch status, ethnicity, gender, English learner) for student i in classroom j, $\beta_{0j} =$ intercept for the jth classroom, $\beta_{1j} =$ slope for the jth classroom and $r_{ij} =$ random error associated with student i in classroom j.

Then the coefficient and intercept in equation 4 (β_{0j}, β_{1j}) are estimated from the data in the level-two data (classroom or school level) as it has been shown in equations 5 and 6

$$\beta_{0j} = \gamma_{00} + \gamma_{01} G_j + U_{0j} \tag{5}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11} G_j + U_{1j} \tag{6}$$

Where β_{0j} = intercept for the jth classroom, β_{1j} = slope for the jth classroom, G_j = environmental data for classroom j, γ_{00} = overall mean intercept adjusted for demographic (student-level) data, γ_{10} = overall mean intercept adjusted for demographic (student-level) data, γ_{01} = slope associated with demographic data (student-level) relative to environmental data (classroom-level) intercept, γ_{11} = slope associated with demographic data (student-level) relative to environmental data (classroom-level) slope, U_{0j} = random effects of the jth classroom adjusted for demographic data (student-level data) on the intercept and U_{1j} = random effects of the jth classroom adjusted for demographic data (student-level data) on the slope.

Finally, by using equations 5 and 6 in equation 4 the mixed model for two levels of data (classrooms level and student level) can be obtained as:

$$\boldsymbol{Y_{ij} = \gamma_{00} + \gamma_{01} G_j + U_{0j} + \gamma_{10} X_{ij} + \gamma_{11} G_j X_{ij} + U_{1j} X_{ij} + r_{ij}} \tag{7}$$

Where Y_{ij} = Mathematics or reading score for student i in classroom j, X_{ij} = demographic data (lunch status, ethnicity, gender, English learner) for student i in classroom j, r_{ij} = random error associated with student i in classroom j, G_j = environmental data for classroom j, γ_{00} = overall mean intercept adjusted for demographic (student-level) data, γ_{10} = overall mean intercept adjusted for demographic (student-level) data, γ_{01} = slope associated with demographic data (student-level) relative to environmental data (classroom-level) intercept, γ_{11} = slope associated with demographic data (student-level) relative to environmental data (classroom-level) slope, U_{0j} = random effects of the jth classroom adjusted for demographic data (student-level data) on the intercept and U_{1j} = random effects of the jth classroom adjusted for demographic data (student-level data) on the slope.

3.8.2. Statistical models

The data grouped into two categories based on grade levels and each group was analyzed separately. Students in grades 3 and 5 were grouped into one (elementary school students) and students in grades 8 and 11 were grouped into another group (middle/ high school students). For each group, two separate models, one for mathematics scores and one for reading scores were created to explore the associations between students' scores with environmental, demographic, and performance variables.

Elementary school student’s data were analyzed at the classroom level and middle/ high school students were analyzed at the school level. Elementary school students spend the whole day in one classroom while middle and high school students use multiple classrooms in one school day. Elementary students are exposed to only one classroom environment, while middle/ high school students are exposed to multiple classroom environments during the school day. In the elementary school model, student-level and classroom-level were used to build the model while in the middle/ high school model two levels of student-level and school-level were used to build the hierarchical linear model.

For the demographic data, binary values were assigned for gender, lunch-pay status, English learners, and ethnicity (Table 11). For gender, the male is assigned a value of 0 and female, 1. Students on free or reduced lunch were assigned a value of 1 and full-pay students, 0. This variable is used as an indicator of the student's economic condition (free-reduced lunch as low-income families and paid-lunch students as high-income families). Due to the majority of students in the studied classrooms being of Caucasian ethnicity, they were grouped as white students, assigned a value of 0, and non-white students, 1. English Language Learner students were assigned a value of 1 and other students were assigned a value of 0.

To determine the interactions between environmental variables and high/ low performer students separate binary variables were created based on student's performance within a classroom. Four new performance variables were created; 1) Top 25% of students in mathematics scores in each classroom as high-performs in mathematics, 2) Top 25% of students in reading scores in each classroom as high-performers in reading, 3) Bottom 25% of students in mathematics scores in each classroom as low-performers in mathematics, 4)

Bottom 25% of students in reading scores in each classroom as low-performers in reading (Table 11).

In each model for elementary and middle/ high schools, IAQ and TC variables, performance, and demographic variables were used as inputs and students' scores (mathematics or reading scores) were used as response variables. Reading performance variables were used for reading models and mathematics performance variables were used for mathematics models. Because of different ranges of values in multiple IAQ and TC variables, these data were standardized by subtracting the mean and dividing by the standard deviation of each variable.

Table 11.Binary values for demographic and performance variables

		Yes	NO
Demographic Variables	Lunch-pay Status = Free-Reduced Lunch	1	0
	Ethnicity = White	1	0
	Gender = Female	1	0
	English Language Learner	1	0
Performance Variables	High-performer (in reading)	1	0
	High-performer (in mathematics)	1	0
	Low-performers (in reading)	1	0
	Low-performer (in mathematics)	1	0

Interactions with demographic and performance variables (e.g., gender, English learners, free-and-reduced lunch students, high-performers, and low-performer) were also explored. Because of increasing model complexity, interactions were first considered one variable at a time in separate sub-models. That is, demographic and performance variables were permitted to moderate the association of one variable and its effects on math and reading achievement. Statistically significant interaction effects from these sub-models were retained in the final model and added to the model.

Chapter 4. Results & Discussion

4.1. Results (Research Question 1)

The results of research question are introduced in this section: "How different the ventilation rate estimations based on various CO_2-based methods? Which method has the least uncertainty for estimating ventilation rates in classrooms?".

Figure 13 shows a typical CO_2 concentration diagram using an average of three sensors, sampled every five minutes over a 36-hour measurement for a classroom. The indoor CO_2 concentration increases as students enter and it starts to decay after dismissal. The indoor CO_2 ranges are similar in three seasons, ranging between 540 ppm to 2300 ppm (Figure 14).

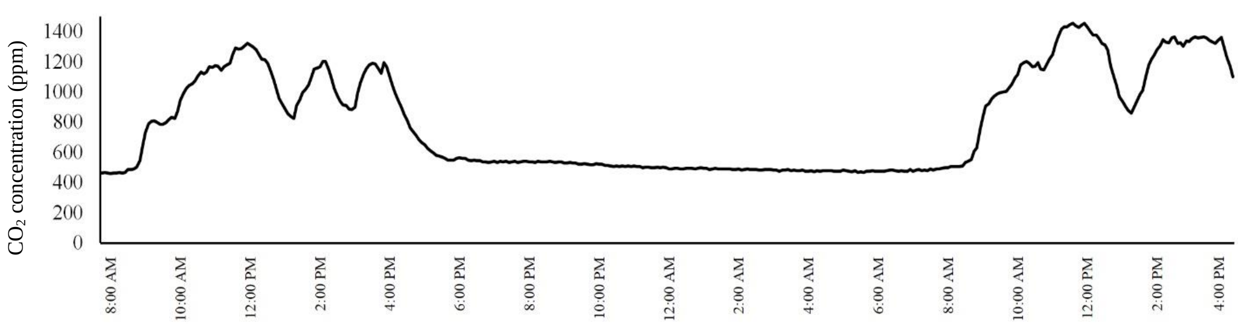


Figure 13. Illustration of a typical CO_2 concentration profile in classrooms over a 36-hour period

Based on communication with the school district, in most of the classrooms, the ventilation systems were kept running until around 5 p.m. With school dismissal around 3:30 p.m., there is about one to two hours to monitor CO_2 concentration during the decay (unoccupied) period. The range of outdoor CO_2 concentration was between 310 ppm to 560 ppm in different seasons.

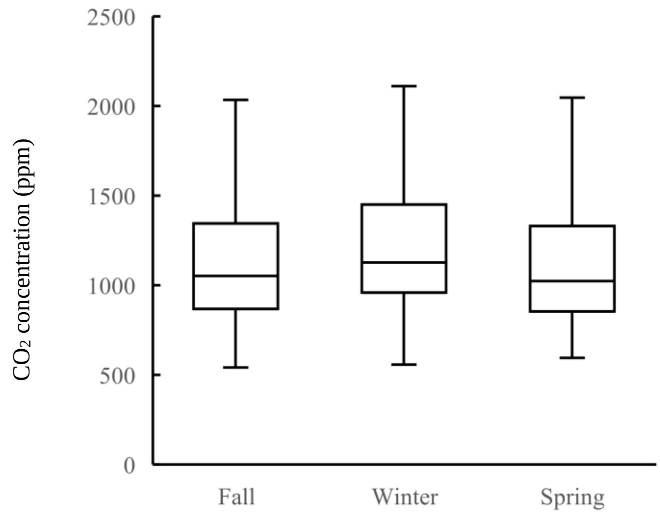


Figure 14. Average CO_2 concentration during occupied hours

As presented in Figure 15(a), estimated ventilation rates (L/s·person) in winter ranged from 0.1 to 18 for the build-up method, 0.05 to 5 for the decay method, and 1.6 to 16 for the steady-state method. In spring (Figure 15(b)), they ranged from 0.05 to 26 for the build-up method, 0.1 to 6 for the decay method, and 1.6 to 11 for the steady-state method. In the fall, as shown in Figure 15(c), they ranged from 0.3 to 23, 0.2 to 6, and 1.6 to 13 for the build-up, decay, and steady-state methods, respectively.

The estimated ventilation rates in fall were similar to those in spring for all three methods, while the ventilation rates were lower and the variation smaller in winter. Ventilation rates estimated by the build-up method were generally the highest values in all three seasons for all classrooms, while those calculated from the decay method were generally the lowest values. An ANOVA test showed a significant difference (p-value < 0.01) between estimated ventilation for these three methods.

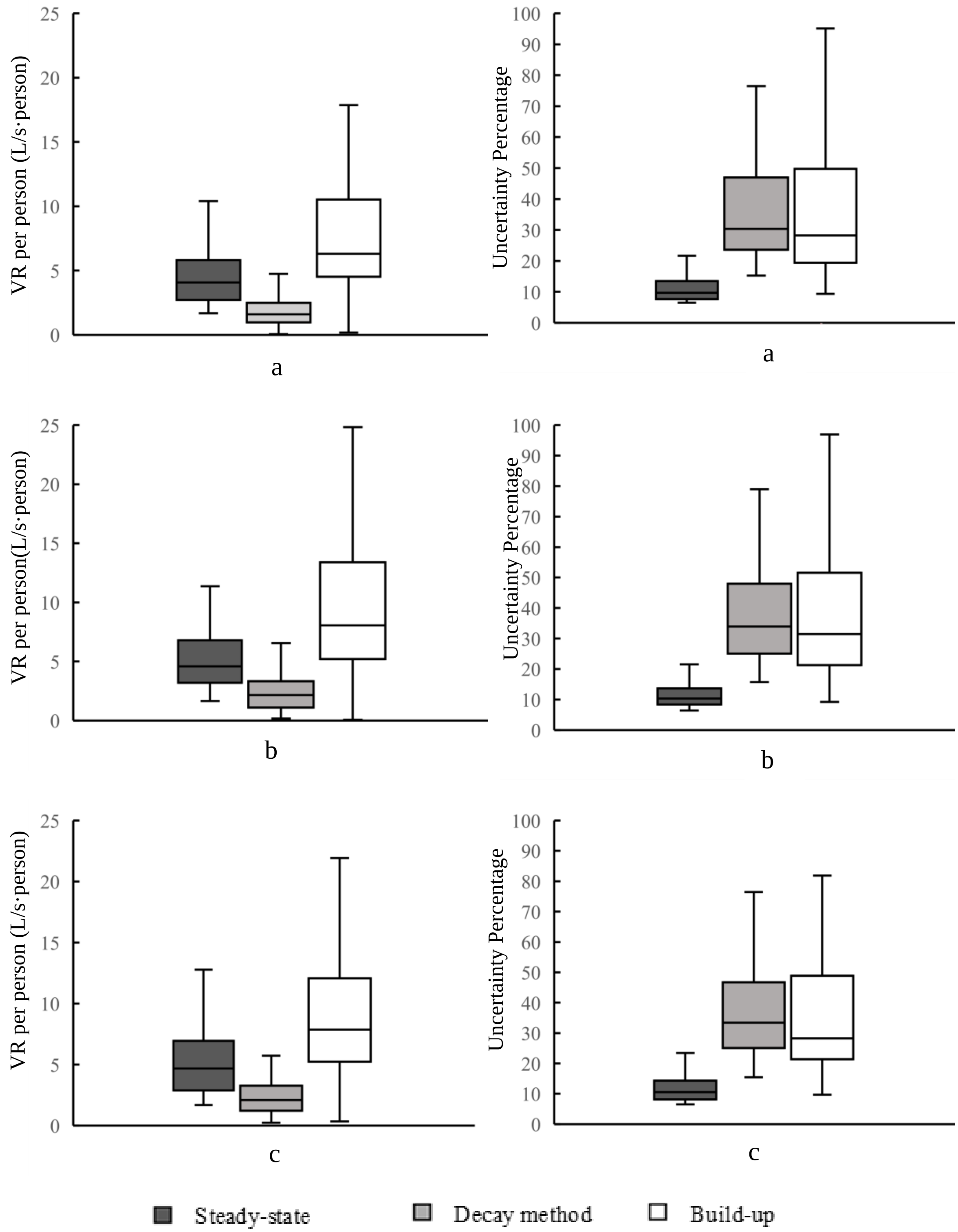


Figure 15. The range of VR and uncertainty (after eliminating outliers) by three methods in three seasons: (a)winter, (b) spring, (c) fall

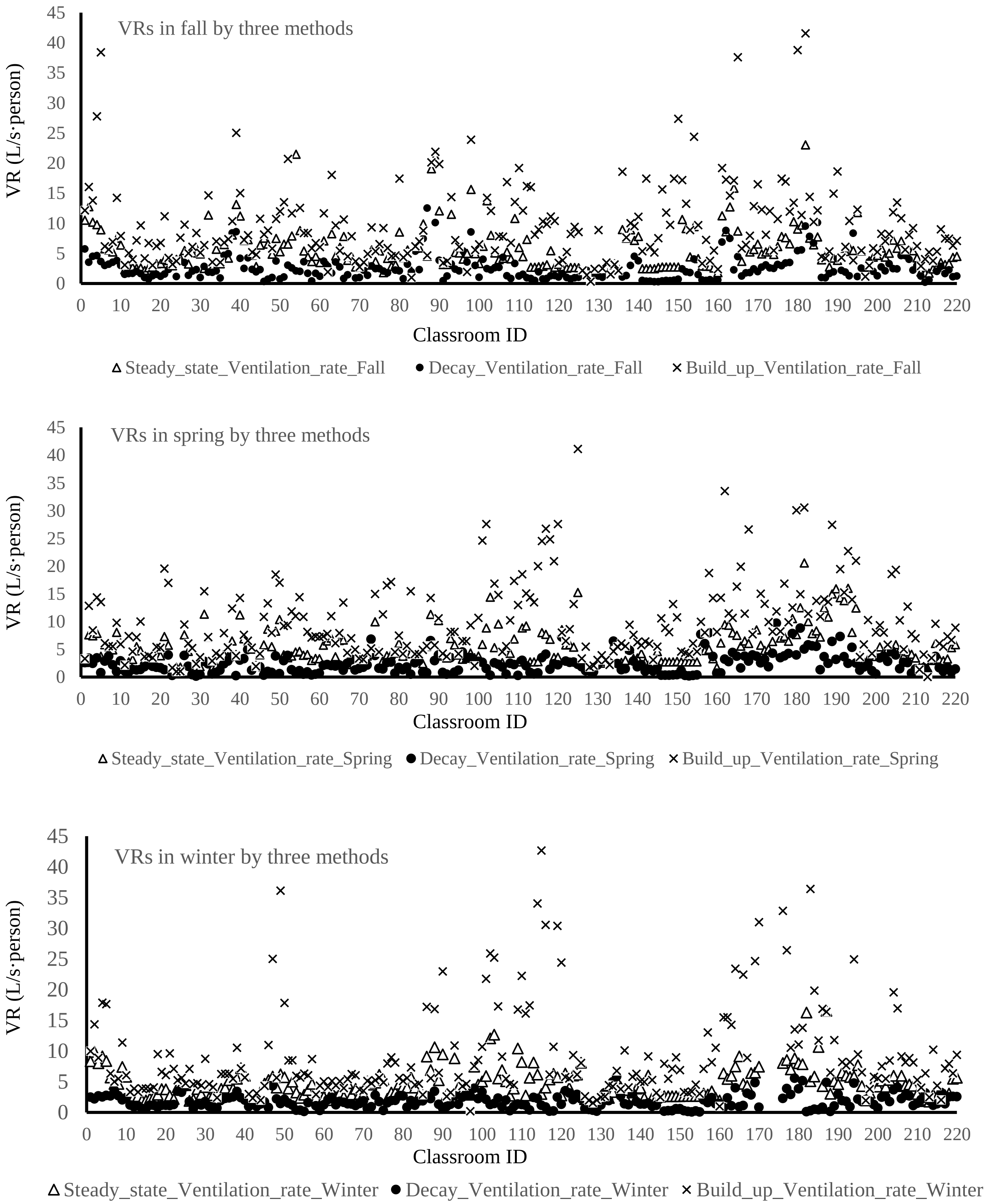


Figure 16. VRs in different seasons by three methods

Uncertainty analysis of these three methods reveals that the steady-state method had the lowest uncertainty when compared to the decay and build-up methods in our study. As it can be seen in Figure 15. a, the uncertainty range for estimated VRs is 6-23% for steady-state, 10-95% for build-up method, and 16-77% for the decay method in winter. The range of uncertainty in spring is 6-23% for steady-state, 15-80% for decay, and 10 to > 95% for build-up (Figure 15. b). Uncertainty ranges in fall are from 6- 23%, 15- 77% and 10- 80% for steady-state, decay, and build-up methods, respectively (Figure 15. c).

Table 12 shows the effect of each variable on the calculation of uncertainty based on each method. In the steady-state method, $C_{steady\text{-}state}$ contributes to the largest portion of uncertainty, in the decay method C_0 is the largest contributor to uncertainty, and in the build-up method, C_t contributes the largest portion of uncertainty. According to these results, G_P and V have the smallest portion of uncertainty in these methods.

Table 12. Order of the effect of each variable on the uncertainty (highest to lowest)

Method	Uncertainty contributing factors (largest to smallest)
Steady-state	$C_{steady\text{-}state} > C_{outdoor} > G_P$
Decay	$C_0 > C_{outdoor} > V > C_1$
Build-up	$C_t > C_{outdoor} > C_0 > C_1 > V > G_P$

Figure 17, shows the comparison of a single zone and multizone estimated ventilation rates with three methods. The variances of VR are smaller in multizone systems when compared to single-zone systems. This could be because of better overall mixing and control approaches in multizone systems. However, the methods discussed in this study were intended to be used in single zone systems as defined in ASTM (ASTM International, 2019).

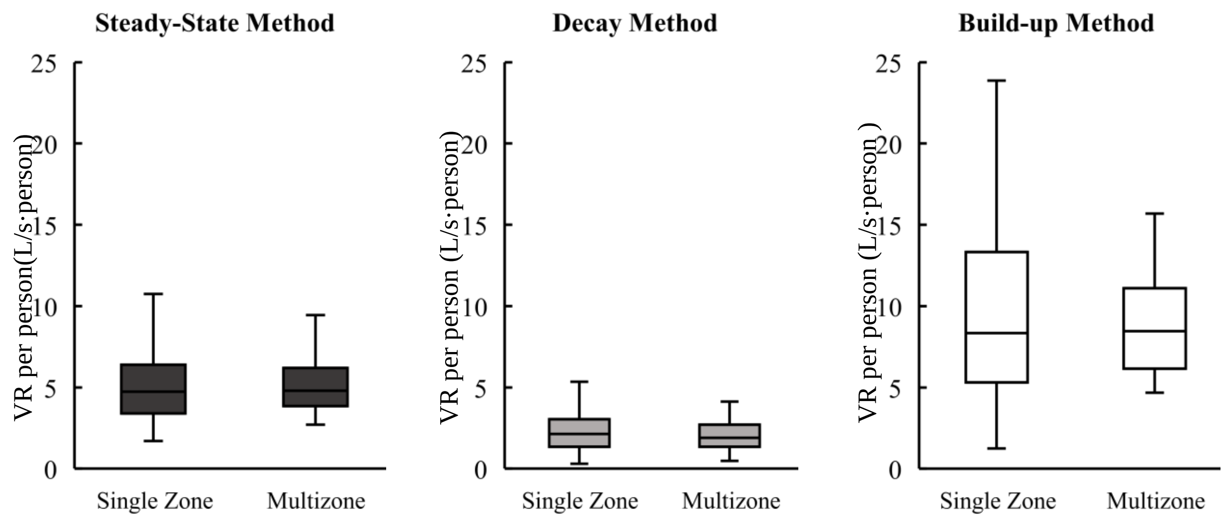


Figure 17. comparison of single zone and multizone estimated VRs with three methods.

4.2. Discussion (Research Question 1)

This research presents ventilation rates and their uncertainty based on CO_2 measurements of 220 classrooms in the Midwestern region of the US. From the uncertainty analysis, for the same measurement variables used in these three methods, the same measurement accuracy ranges were applied, and outlier data have been removed from the estimated ventilation rates.

Different tracer gases in previous studies have been used to estimate ventilation rates. SF_6 and CO_2 are the most adopted tracer gases. Since the occupant densities are high in the studied classrooms, CO_2 concentration is appropriate to estimate ventilation rates (Ha, 2012), however, using indoor CO_2 concentration is based on several assumptions that may not be valid for a given space. To minimize the inaccuracies due to imperfect mixing, multiple indoor CO_2 sensors were used in different locations for each classroom, and the average recorded values were used. For classrooms, in the same school, at least two outdoor sensors were used to measure outdoor CO_2 concentration. In cases with sensor malfunctions due to extremely low outdoor temperature during winter, indoor CO_2 concentrations from 3 to 5 a.m. were substituted for the outdoor CO_2 concentration because it was assumed that indoor CO_2 concentration is approximately equal to outdoor CO_2 concentration when the spaces were unoccupied for over 12 hours (in the early morning). It was assumed that the number of students, VR, and outdoor CO_2 were constant during occupied periods. The research team validated these assumptions by using occupancy numbers based on actual attendance, real-time monitoring of outdoor CO_2 levels averaged over the calculation period, and eliminating data taken after 5 p.m. when mechanical systems were likely turned off. Also, classrooms with no external doors or operable windows were chosen for the measure.

In this analysis, volume measurement with 10% uncertainty was assumed. The volumes of classrooms were calculated by multiplication of length, width, and height of the classroom. Small deformations in the shape of the room (from a cube) can cause uncertainty in the volume of the room. Moreover, the furniture and other content in the classrooms reduced the measured ventilation space in classrooms. The authors suggest that a follow-up investigation is needed to evaluate the tracer gas methods, with and without furniture in a controlled space.

Referring to Figure 16 there was a smaller variance in ventilation rates in multizone systems when compared to single-zone systems. The CO_2 concentration of supply air in multizone systems (such as VAV) is influenced by the recirculated airflows from other zones. Mixing the return air from all other ventilated zones may have changed the CO_2 concentration at the supply air. According to Figures 14 and 15, estimated ventilation rates are lower in winter compared to fall and spring seasons. Low VRs in winter might be caused by school staff over-riding the outdoor air damper settings as a short-term (or low-cost) solution to address complaints. Another possible explanation may be that schools leave doors or windows open more often during fall and spring which promotes infiltration.

In school environments, most of the previous research studies used a steady-state method (U. Haverinen-Shaughnessy et al., 2011a; Ulla Haverinen-Shaughnessy et al., 2015; Mendell et al., 2013; Shendell et al., 2004b). According to a study by Cui et al (Cui et al., 2015), the results of decay and steady-state methods are compatible, however, a paired t-test, on the results, showed a significant difference (p-value < 0.01) between these methods. According to Sherman, the build-up method can overestimate ventilation rates by as high as 15– 35 % (Sherman, 1989). The build-up method has the most variables in the equation while the steady-state method has the least variables as shown in Table 4. This may explain the smaller uncertainty for the steady-state method when compared to build-up and decay methods. In particular, the number of students was accurately counted (so, the error was assumed to be zero). However, error due to CO_2 sensors is about 5% of the reading, and both build-up and decay methods used multiple CO_2 readings in the calculation processes. Also, there may be errors in selecting the start-time and end-time for the build-up and decay methods. Calculated ventilation rates from the decay method had the lowest values.

Since CO_2 measurements contributed to the largest portion of uncertainty from this study, the authors would like to give some recommendations for field measurements using CO_2 as a tracer gas. First, using multiple CO_2 sensors is encouraged to reduce the chances of missing data due to equipment failure. The authors also recommend placing CO_2 sensors in supply and return ducts to get a more representative reading. In this study, since accessing the ducts was intrusive and requires extra supports and approval from school staff, the research team decided to place sensors next to supply diffusers and return grills. Regarding occupant data, the gender and age of the students should be included in order to decrease uncertainty for the CO_2 generation rate. Using thermal cameras is also suggested for an accurate record of the occupant count and to better determine activity levels in the room.

4.3. Results (Research Question 2)

The results of the following research question are introduced in this section: "Do indoor air quality, thermal environmental factors vary on the classroom level or the variations are limited to the school level?"

4.3.3.Analysis of Variance (ANOVA):

To determine the variability between measurements in each school an analysis of variance (ANOVA) was performed. Table 16 shows the results of ANOVA on classrooms of each school. According to the ANOVA results in 30.55 % of schools with single-zone systems CO_2 concentration (or estimated ventilation rates) between classrooms are significantly different. Other variables with a significant difference between measurements within classrooms in the single-zone schools are coarse particles, air velocity, temperature, Ozone, fine particles, globe temperature, and TVOC. In single-zone schools, relative humidity, CO, formaldehyde, and NO_2 don't have any variability between classrooms.

In classrooms with multi-zone systems in 25% of schools globe temperature measurements were significantly different between classrooms. Other variables with a significant difference between measurements within classrooms in the multi-zone schools are CO_2 concentration (or estimated ventilation rates), temperature, and velocity. In multi-zone schools, no significant difference between particles, relative humidity, CO, formaldehyde, Ozone, TVOC, and NO_2 was observed.

Table 13. Number of schools in which the IAQ, TC variables have significant variability between classrooms

Single-zone Schools (sample size = 36)		
Variable	**Number of schools** **(with a significant difference between classroom measurements)**	**Percentage (%)**
CO_2 (or estimated ventilation rates)	11	30.55
pn_coarse	8	22.22
velocity	7	19.44
temperature	5	13.88
Ozone_indoor	4	11.11
pn_2.5	4	11.11
globe_temperature	3	8.33
TVOC	3	8.33
Multi-zone Schools (sample size = 8)		
Variable	**Number of schools** **(with a significant difference between classroom measurements)**	**Percentage (%)**
globe_temperature	2	25.00
CO_2 (or estimated ventilation rates)	1	12.50
temperature	1	12.50
velocity	1	12.50

4.3.3.1.Ventilation

Figure 18 shows the range of seasonal ventilation rates in each school. Classrooms' ventilation rates in each school have a wider range in spring and fall compared to winter. According to ANOVA results Statistically significant differences were found in ventilation rates of 12.5% of schools with multi-zone systems while in 30.55% of schools with single-zone systems the ventilation rate was found significantly different.

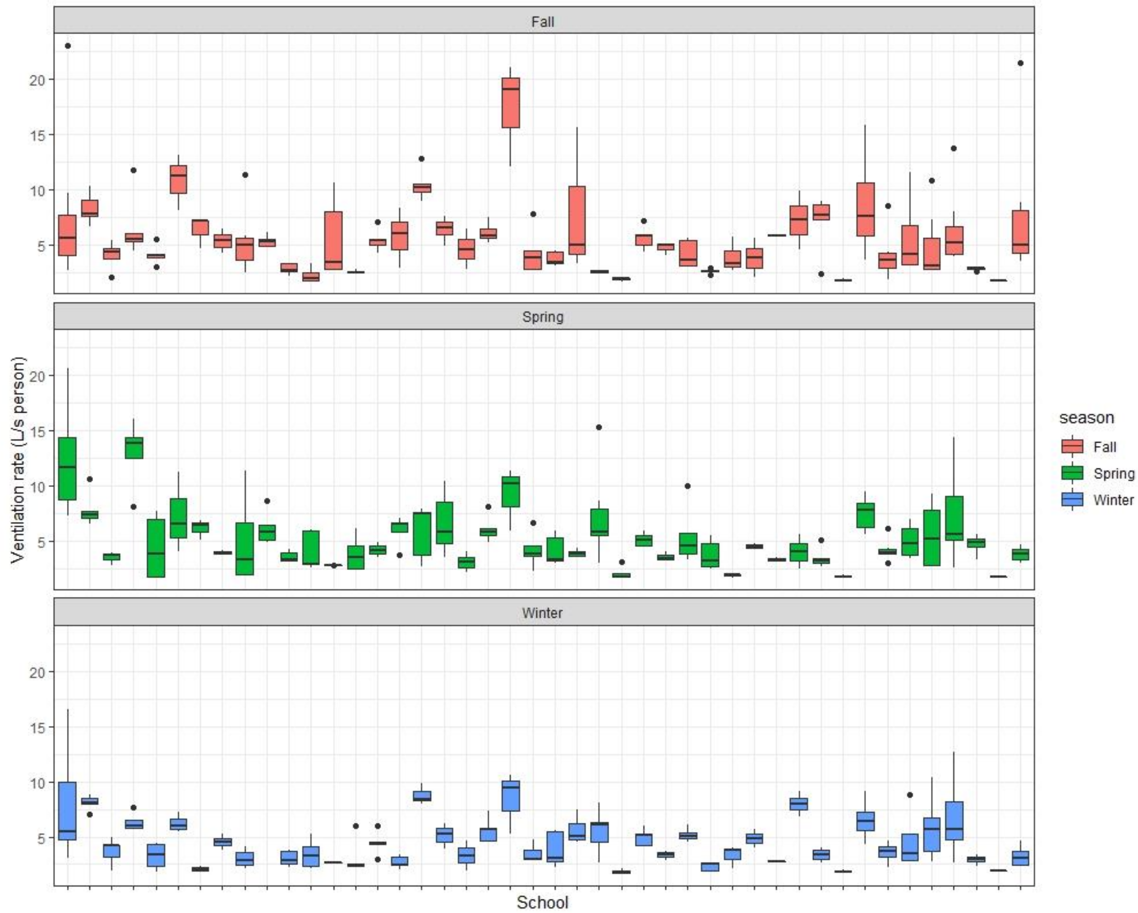


Figure 18. The range of seasonal ventilation rates in each school

4.3.3.2.Globe Temperature

Figure 19 shows the range of seasonal globe temperatures in each school. Classrooms globe temperatures in each school have a narrower range in spring comparing to fall and winter. The results of ANOVA show the difference between means of classrooms' globe temperatures are statistically significant in 25.00% of schools with multi-zone systems and 8.33% of schools with single-zone systems.

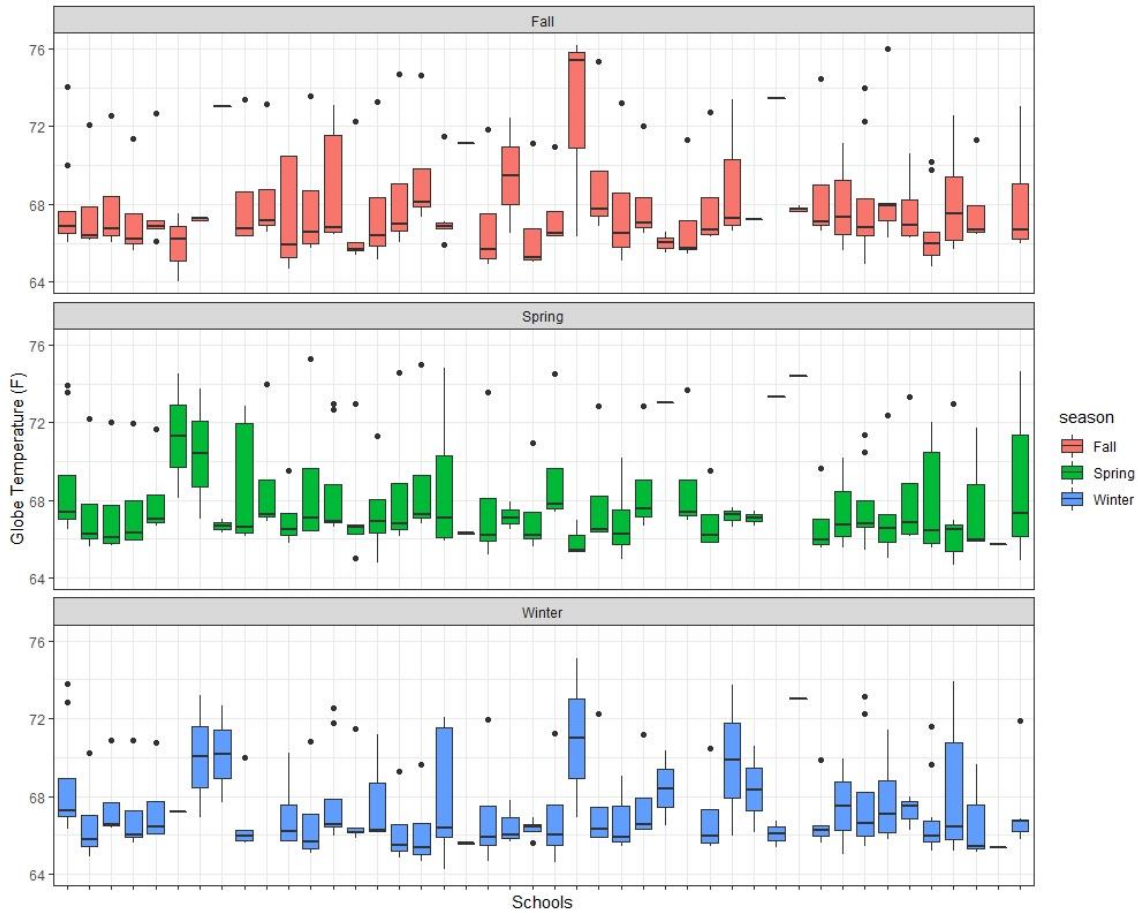


Figure 19. The range of seasonal globe temperatures in each school

4.3.3.3.Temperature

Figure 20 shows the range of seasonal indoor temperatures in each school. Classrooms' indoor temperatures in each school has a wider range in winter comparing to spring and fall. The results of ANOVA show the difference between means of classrooms' indoor temperatures are statistically significant in 12.50% of schools with multi-zone systems and 13.88% of schools with single-zone systems.

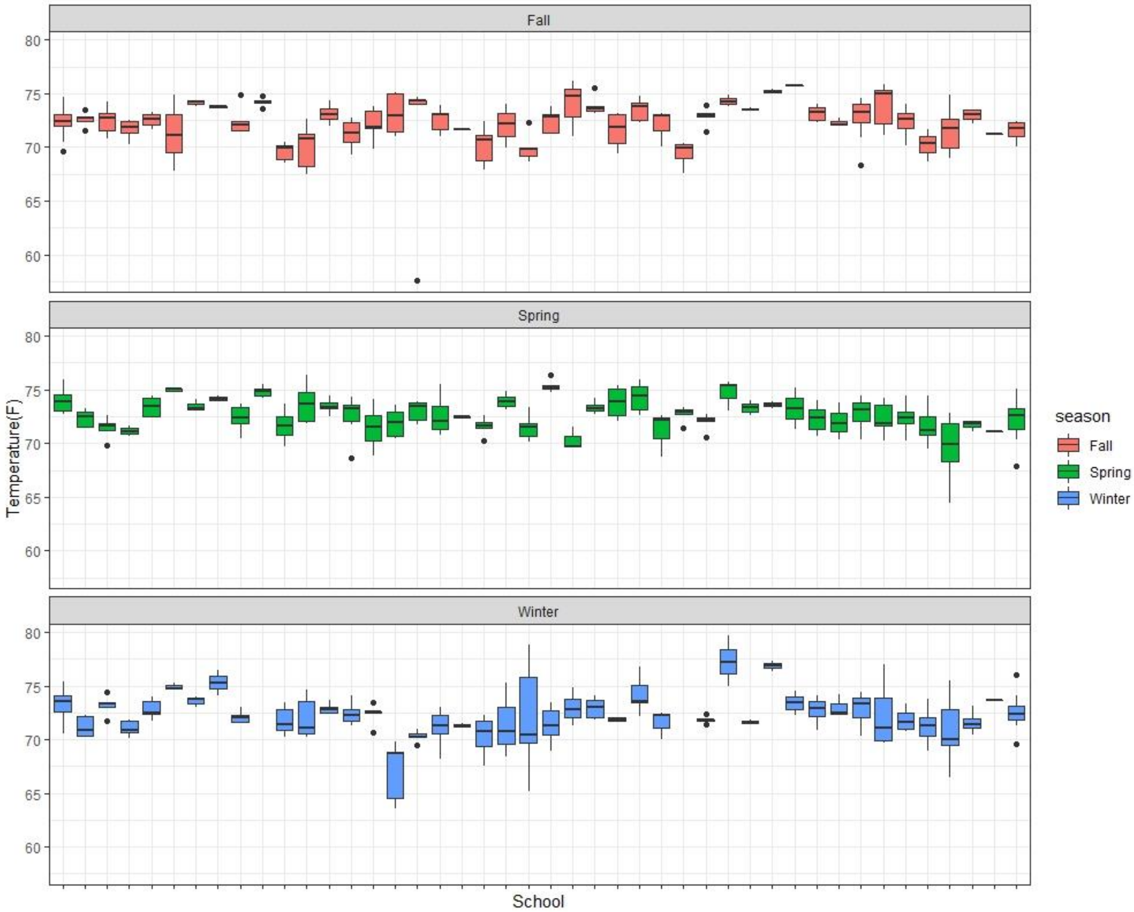


Figure 20. The range of seasonal temperatures in each school

4.3.3.4.Fine Particles

Figure 21 shows the range of fine particle counts in each school. Two schools have an abnormally high concentration range of fine particles. The results of ANOVA show that the difference between means of classrooms' fine particles is statistically significant in 11.11% of classrooms with single-zone. No statistically significant difference between means of classrooms in schools with multi-zone systems was found.

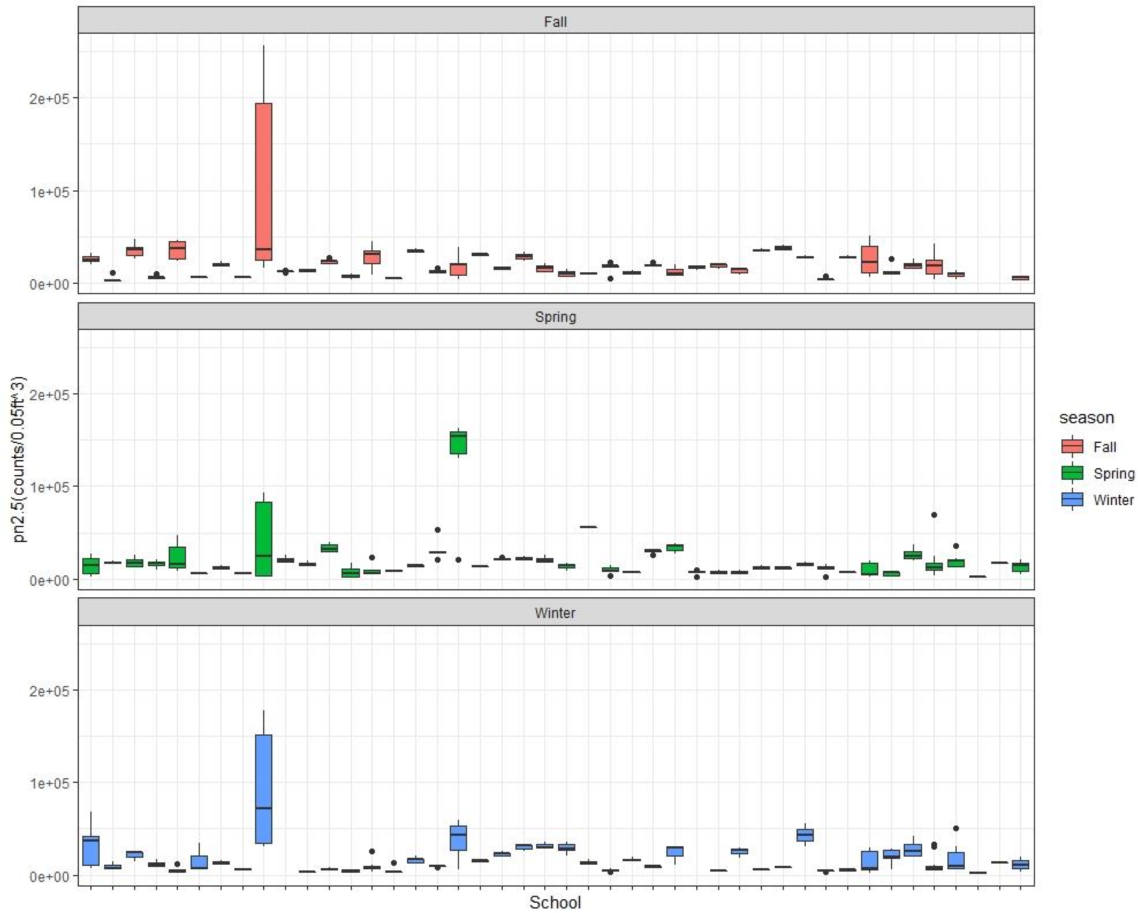


Figure 21. The range of seasonal fine particles in each school

4.4.Discussion Research Question 2

This study explores the variability of IAQ, TC factors in schools, and investigates if these factors vary on the classroom level or the variations are limited to the school level. CO_2 concentration (or estimated ventilation rates) in single-zone schools have the highest variability between classrooms, however, in schools with multi-zone systems, less variability between classrooms' CO_2 concentration was observed. In single-zone schools, coarse particles and air velocity have also a high variability within classrooms of a school, while in schools with multi-zone systems, no significant variation in particle concentration between different classrooms was observed. Comparing to single-zone, multi-zone systems serve multiple classrooms and that may be the reason for classrooms' CO_2 concentration, coarse particles, and air velocity to be more consistent in multi-zone systems. Based on the results of this study in the schools with multi-zone systems, fewer CO_2 concentrations, coarse particles, and air velocity measurements may be sufficient to represent the entire condition of the schools.

In the schools with multi-zone systems, globe temperature has the most variability between classrooms of a school. Comparing to globe temperature, the temperature has less variability between classrooms. This may be explained by the radiation effect measured by globe temperature. Even though mechanical systems (multi-zone or single-zone) systems can provide an almost consistent air temperature in classrooms of a school but radiation in classrooms (e.g. sun rays, cold or hot surfaces) may influence the globe temperature of a classroom. According to ASHRAE Std 55, globe temperature may be a better representative of thermal sensation when comparing to air temperature. Higher priority should be giving to measuring indivudial globe temperature in each classroom while air temperature can be measured at the school level for the schools with multi-zone systems.

This study was performed based on limited sample size (8 schools with multi-zone systems and 36 schools with single-zone systems), therefore the percentage of schools in which a variable is determined significant was used to compare the results between single-zone and multi-zone systems. Unit ventilators and centralized systems with variable air volume (VAV) or air handling units (AHU) are the main air side HVAC systems that serve the studied classrooms. Heat pumps and unit ventilators grouped together as “single-zone” systems. However, the results may vary depending on the type of single-zone system in schools. More studies with larger sample sizes can help indoor environmental quality researchers to prioritize their multiple measurements within a school building and to select the variables with the most variability.

4.5. Results (Feature Selection)

In this section the results of correlation study and omnibus test are introduced. These results are used to select features to build statistical models in this study.

4.5.1. Correlation study

The correlation study for variables measured continuously during the classroom’s occupied time has been reported in the below section. The correlation coefficient (R) and p-value between variables in two different seasons (fall vs spring, winter vs spring, and fall vs winter) have been shown in each figure. A box plot is used to show the range of variables in each season. Below are the selected correlation study and figures. The rest of variables’ correlation study can be found in appendix A.

4.5.1.1. Ventilation rates

The boxplot in figure 22 shows the range of ventilation rate in each season. Ventilation rates in fall have a minimum of 1.68 Lit/s. person and a maximum of 23.05 Lit/s. person with a mean of 5.55 lit/s. person. Ventilation rates in winter have a minimum of 1.65 Lit/s. person and a maximum of 20.60 with a mean of 5.41 Lit/s. person. Ventilation rates in spring have a minimum of 1.67 and a maximum of 16.54 with a mean of 4.61.

According to figure 22 ventilation rates in fall and ventilation rates in spring are significantly correlated with a correlation coefficient of 0.55 and p-value less than 0.01. Ventilation rates in the winter and spring season are significantly correlated with a correlation coefficient of 0.59 and a p-value less than 0.01. Ventilation rates in the fall and winter seasons are significantly correlated with a correlation coefficient of 0.4 and a p-value less than 0.01.

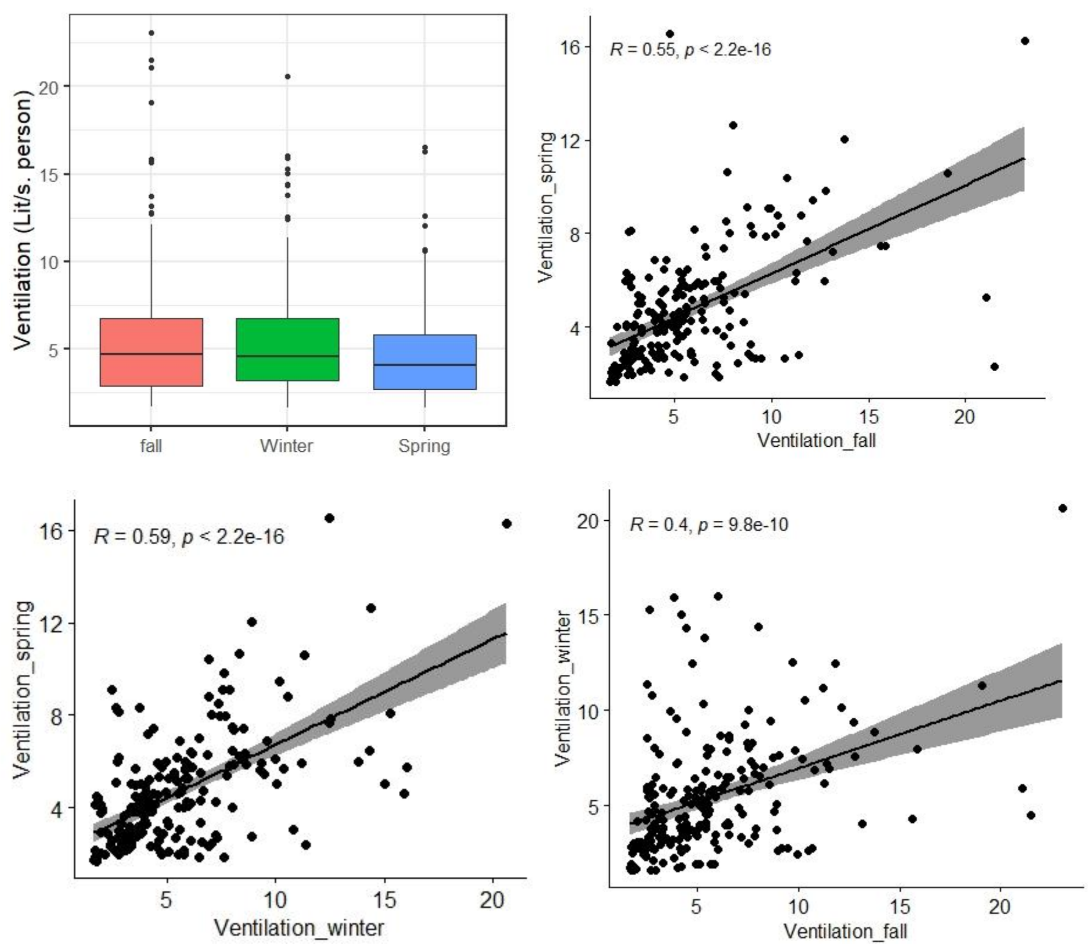


Figure 22. Ventilation rate range and correlations in three season

4.5.1.2. Globe temperature

The boxplot in figure 23 shows the range of globe temperature in three seasons. Globe temperature in fall has a minimum of 64.02 ˚F and a maximum of a 76.19 ˚F with a mean of 68.05 ˚F. Globe temperature in winter has a minimum of 64.64 ˚F and a maximum of 75.28 ˚F with a mean of 68.04 ˚F. Globe temperature in spring has a minimum of 64.25 ˚F and a maximum of a 75.07 ˚F with a mean of 67.43 ˚F.

According to figure 23 globe temperatures in fall and spring are significantly correlated with a correlation coefficient of 0.33 and p-value less than 0.01. Globe temperatures in winter and spring are not correlated since the p-value is greater than 0.05 (significance level). Globe temperatures in fall and winter are not correlated as the p-value is greater than 0.05.

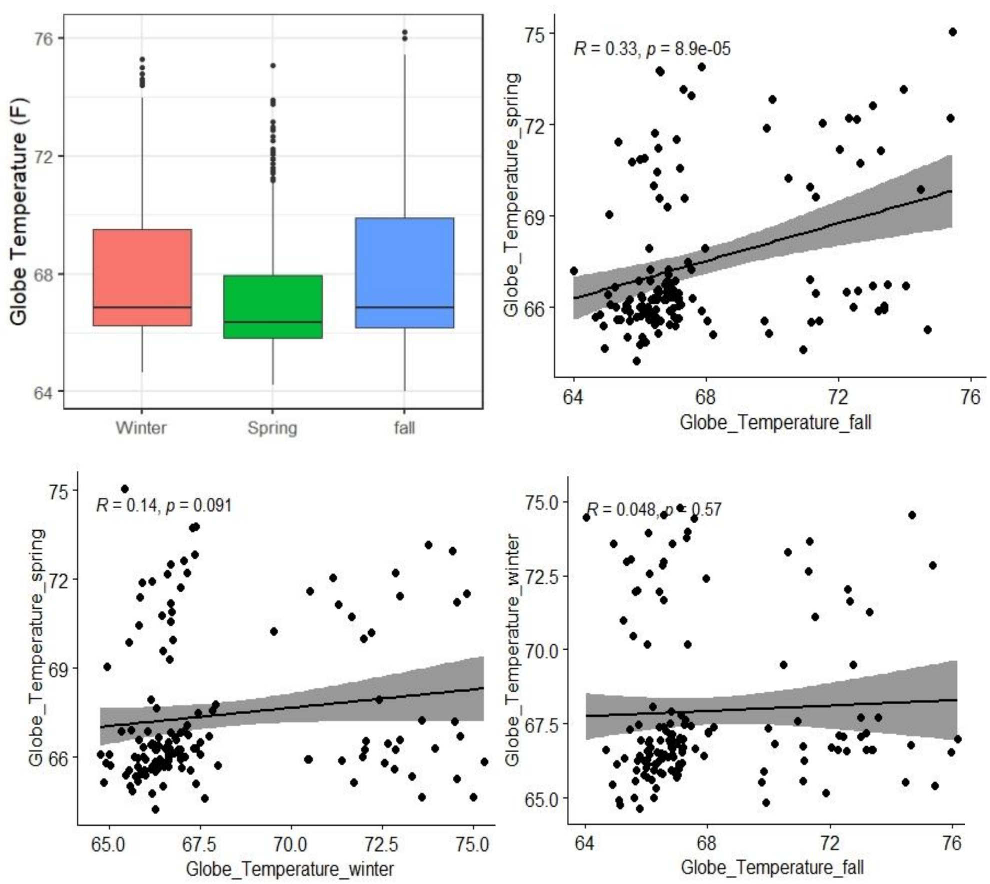


Figure 23. Globe temperatures range and correlations in three seasons

4.5.1.3. Temperature

The boxplot in figure 24 shows classrooms' indoor temperatures range in three seasons. Classrooms' indoor temperature in fall has a minimum of 57.59 ˚F and a maximum of 76.17 ˚F with a mean of 72.21 ˚F. The classrooms' indoor temperature in winter has a minimum of 64.44 ˚F and a maximum of 76.40 ˚F. The temperatures in spring have a minimum of 63.55 ˚F and a maximum of 79.64 ˚F with a mean of 72.19 ˚F.

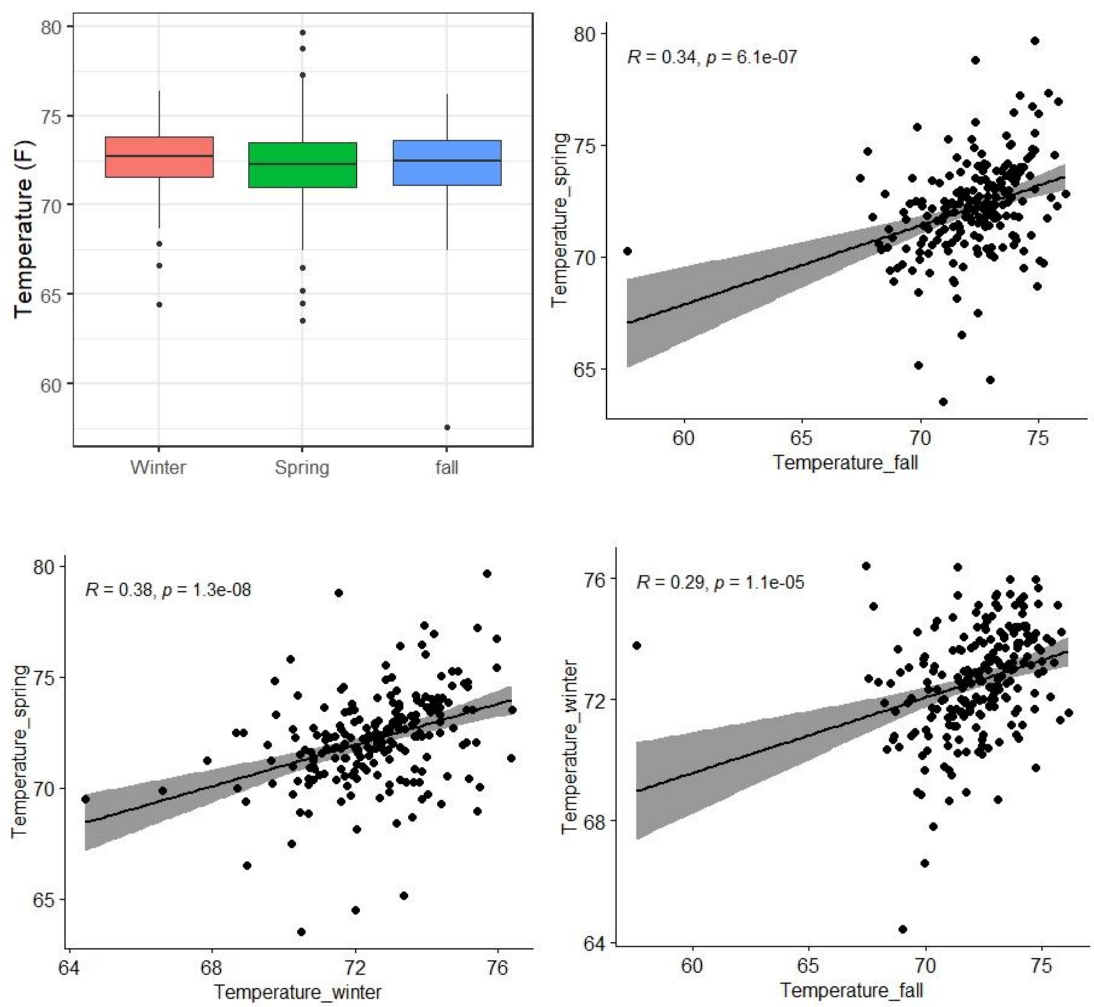


Figure 24. Temperature range and correlations in three seasons

According to figure 24 classrooms' indoor temperatures in fall and spring are significantly correlated with a correlation coefficient of 0.34 and a p-value less than 0.01.

The indoor temperatures in winter and spring are significantly correlated with a correlation coefficient of 0.38 and a p-value less than 0.01. The indoor temperatures in fall and winter are significantly correlated with a correlation coefficient of 0.29 and a p-value less than 0.01.

4.5.1.4. Fine particles

The boxplot in figure 25 shows the range of fine particles in three seasons in classrooms. Fine particles in classrooms in fall have a minimum of 2067 counts per 0.05 ft^3 of the air and a maximum of 47616 counts per 0.05 ft^3 of the air with a mean of 17458 counts per 0.05 ft^3 of the air. Fine particles in winter have a minimum of 1192 counts per 0.05 ft^3 of the air and a maximum of 40493 counts per 0.05 ft^3 of the air with a mean of 14585 counts per 0.05 ft^3 of the air.

According to figure 25 fine particles in the fall and spring season are significantly correlated with a correlation coefficient of 0.16 and a p-value less than 0.05. Fine particles in winter and spring are significantly correlated with a correlation coefficient of 0.22 and a p-value less than 0.01. Fine particles in fall and spring are not correlated since the p-value is greater than the significance level.

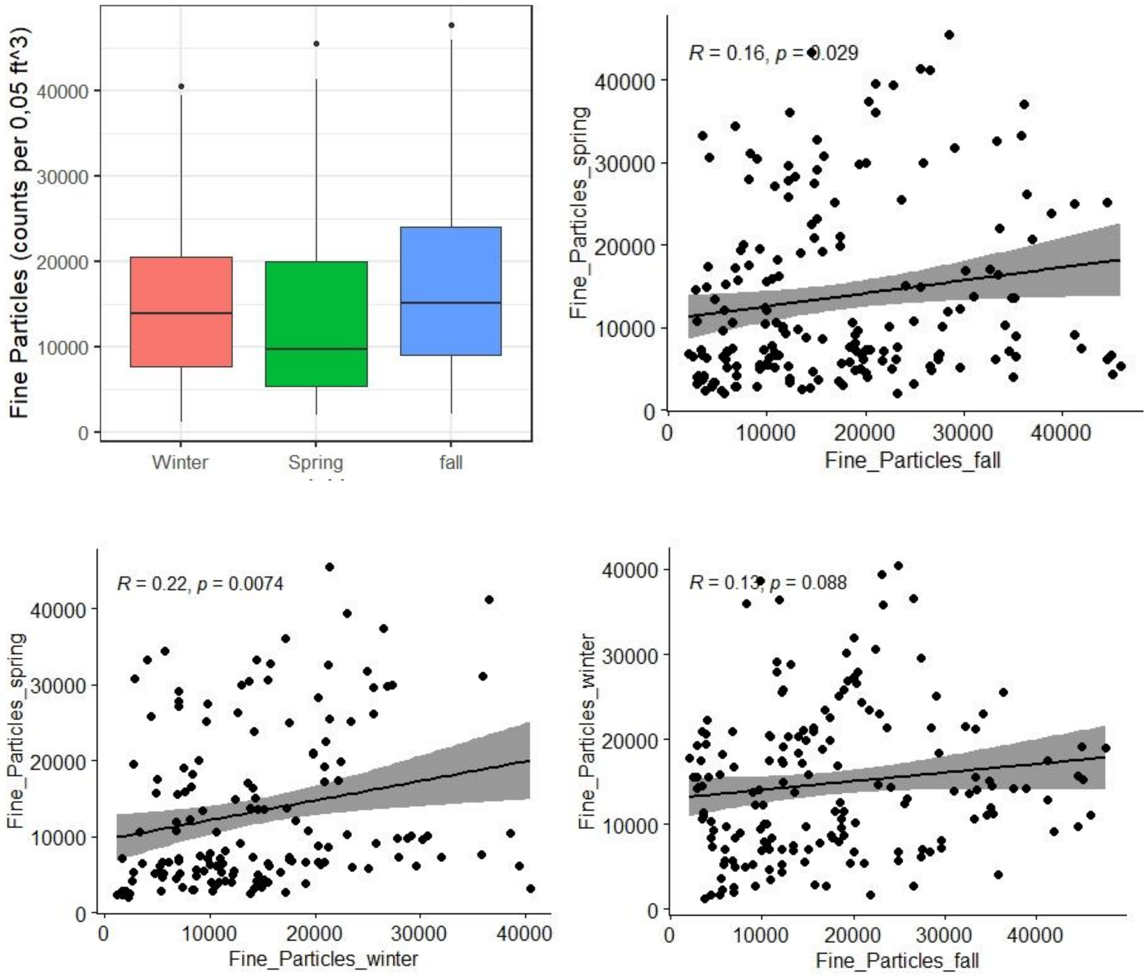


Figure 25. Classrooms' fine particels ranges and correlations in three seasons

4.5.1.5. Relative humidity

The boxplot in figure 26 shows the range of relative humidity in classrooms in three seasons. Relative humidity in fall has a minimum of 20.92% and a maximum of 73.55% with a mean of 50.78%. Relative humidity in winter has a minimum of 19.42% and a maximum of 60.61% with a mean of 39.74%. Relative humidity in spring has a minimum of 14.13% and a maximum of 51.98% with a mean of 28.34%.

According to figure 26 relative humidity in fall and spring are significantly correlated with a correlation coefficient of 0.21 and a p-value less than 0.01. Relative humidity in winter and spring are not correlated since the p-value is greater than the significance level (0.05). Relative humidity in fall and winter are significantly correlated with a correlation coefficient of -0.41 and a p-value less than 0.01.

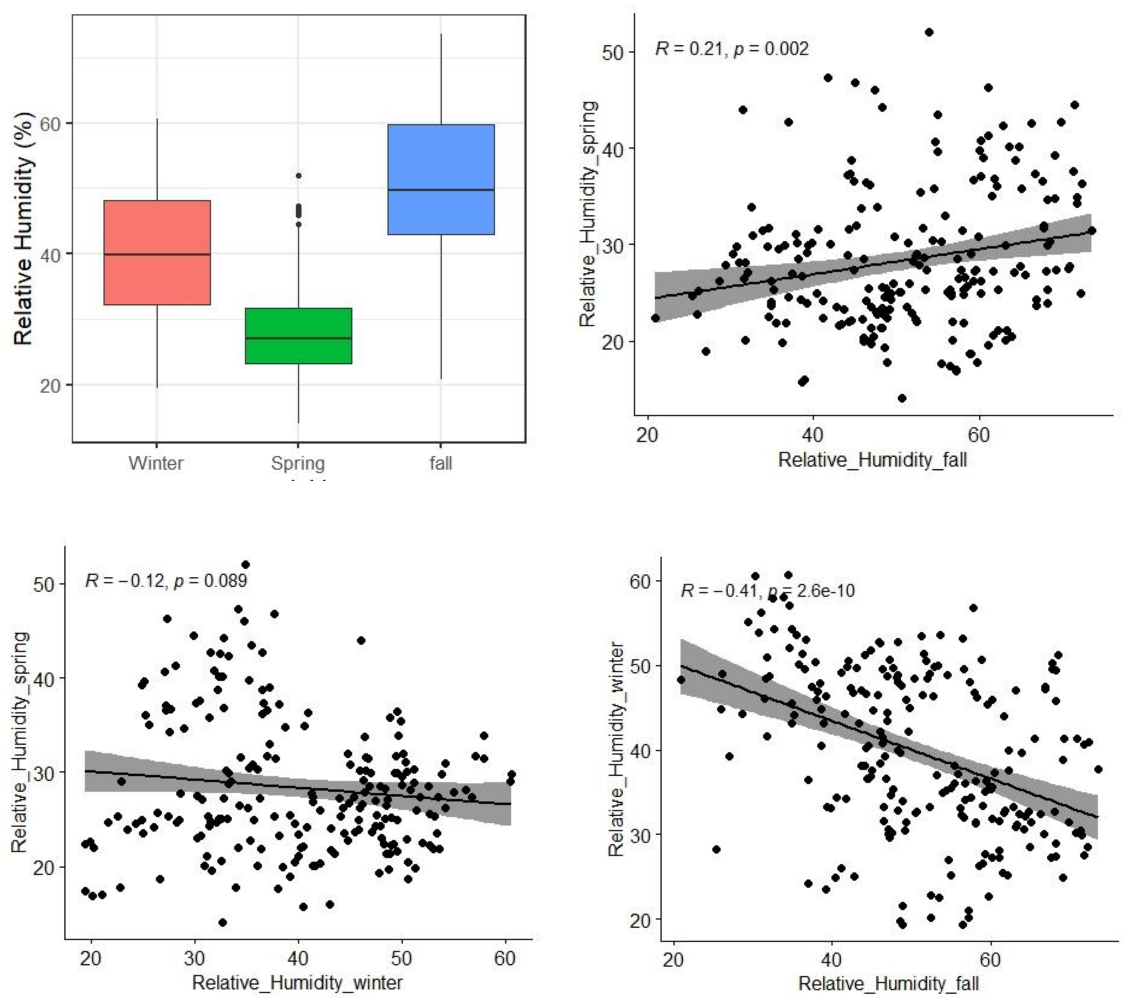


Figure 26. Classrooms' relative humidity ranges and correlations in three seasons.

4.5.1.6. Unoccupied variables

Table 13 shows the results of the correlation study for variables measured during the unoccupied time. For CO, correlations for winter vs spring and fall vs winter are significant (p-value < 0.05). For NO_2 the correlation between fall and winter is significant while for TVOCs the correlations for fall vs spring and winter vs spring are significant. For ozone correlations between all three seasons are significant.

Table 13. Correlation study for unoccupied measurements

Variable	Season	Correlation coefficient (R)	P-value
CO	Fall vs Spring	0.083	0.27
	Winter vs Spring	0.28	< 0.01
	Fall vs Winter	0.3	< 0.01
NO2	Fall vs Spring	-0.11	0.1
	Winter vs Spring	0.027	0.7
	Fall vs Winter	-0.15	0.023
TVOCs	Fall vs Spring	0.28	< 0.01
	Winter vs Spring	0.31	< 0.01
	Fall vs Winter	0.15	0.024
Ozone	Fall vs Spring	0.21	0.004
	Winter vs Spring	0.36	< 0.01
	Fall vs Winter	0.32	< 0.01

4.5.2. Omnibus test

An Omnibus test was performed in an earlier study on the classroom data. Based on the results of the omnibus test the following variables used in the model as seasonal or annual averages in the final model. Table 14 shows the results of the Omnibus test. According to Table 14, fine particles, ventilation rate, temperature, globe temperature, coarse particles, and air velocity were used as seasonal variables in the model. Formaldehyde, coarse particles, relative humidity, CO, NO2, Ozone and TVOC are used as a single variable (without considering seasonal changes) in the model.

Table 14. Input variables used to build the statistical model (continuous variables)

Input Variables	Measurement period	Seasonal/ Annual	Mean	Minimum	Maximum	Standard deviation
Continuous						
Fine Particles (counts/0.05 ft^3)	Occupied	Fall	20008	2067	256510	25400.69
		Winter	16970	2037	176732	21517.85
		Spring	20201	1192	162451	25823.39
Ventilation (Lit/ s.person)	Occupied *(estimated based on CO_2 concentration)	Fall	5.449	1.685	21.500	3.351138
		Winter	4.515	1.671	16.536	2.301533
		Spring	5.344	1.652	16.011	3.002497
Temperature (˚F)	Occupied	Fall	72.24	57.59	76.17	2.072391
		Winter	72.19	63.55	79.64	2.161042
		Spring	72.63	64.44	76.40	1.758044
Globe Temperature (˚F)	Occupied	Fall	68.11	64.02	76.19	2.876749
		Winter	67.46	64.25	75.07	2.511666
		Spring	68.03	64.64	75.28	2.81727
Formaldehyde (ppb)	Occupied	Fall	20.45	8.00	42.00	8.00097
Coarse Particles (counts/0.05 ft^3)	Occupied	Annual	373.03	85.64	1714.24	230.1435
Relative Humidity (%)	Occupied	Annual	39.90	26.08	49.99	4.783333
Air velocity (m/s)	Unoccupied	Fall	0.10494	0.00	0.42133	0.07043865
		Winter	0.08719	0.00	0.52727	0.06361907
		Spring	0.10013	0.00	0.33520	0.06394149
Carbon monoxide (ppm)	Unoccupied	Annual	0.3069	0.0000	1.1667	0.2120509
Nitrogen Dioxide (ppm)	Unoccupied	Annual	0.10433	0.01750	0.16933	0.03008866
Ozone (ppb)	Unoccupied	Annual	7.1900	0.1667	26.7000	4.977735
TVOC (ppb)	Unoccupied	Annual	212.65	96.39	1252.13	121.8925

4.6. Results (Research Question 3)

The results of following research question are introduced in this section:

What are the associations between indoor air quality, thermal environmental factors, and student's academic achievement in different demographic groups?

- Do high-performing and low-performing students respond to IAQ, thermal similarly?
- Do students in different demographic groups respond differently to IAQ, thermal factors?

The results for elementary schools (grade 3 and 5) and middle/ high schools (grade 8 & 11) models were presented separately. Significant variables (p-value < 0.05) in addition to significant interaction effects have been shown for both mathematics and reading scores. Tables 15 to 18 show the summary of results and significant associations and interactions between mathematics, reading scores, and seasonal IAQ, TC factors for elementary and middle/ high school students. Interaction plots for selected demographic variables with a significant level (p-value < 0.05) can be found in appendix B.

4.6.1. Elementary Schools

4.6.1.1. Reading Scores

According to table 15 in the model for elementary schools' reading scores ventilation rate in fall, the temperature in fall, globe temperature in spring and winter, formaldehyde in fall, fine particles in winter, air velocity in winter, annual coarse particles, relative humidity and TVOC concentration in classrooms are significant variables. In this model classroom level was used as the random effect and the Akaike information criterion (AIC) is equal to 2104. According to appendix C, comapring to the model without performance variables (with AIC = 4023.9) the model with performance variables has a lower AIC, and therefore is selected as the final model.

Holding all other variables constant, a lower globe temperature in spring is associated with higher reading scores (p-value < 0.05) while a higher globe temperature in winter is associated with higher reading scores for elementary students. A lower formaldehyde concentration in fall is associated with higher reading scores. A higher fine particle concentration in winter and annual coarse particle concentration is associated with higher reading scores. A lower annual TVOC concentration and lower relative humidity are also associated with higher reading scores for elementary schools.

In this model, interaction effects between ventilation rates in fall, the temperature in fall, and high- performer students, were found. Higher ventilation rates in fall have a greater positive association with high-performer students reading scores while a lower temperature in fall has a greater positive association with high-performers in each classroom. There are also associations between low-performer students and NO_2 concentration, English Learners, and air velocity in winter for elementary school students reading scores.

Table 15. Elementary Schools (Reading Scores)

Model Inputs	Input Variables	Estimate	Standard Error	p-value	Significance level
γ_{00}	(Intercept)	0.0276	0.1563	0.8611	
γ_{10}	system_typeSingle-Zone	0.0798	0.1630	0.6266	
	Gender1	0.0215	0.0246	0.3821	
	Free_Reduced_lunch1	-0.1891	0.0337	0.0000	***
	White_notWhite1	0.0287	0.0430	0.5039	
	English_Learners1	-0.0414	0.0594	0.4857	
	ReadingTop251	1.1320	0.0315	< 2e-16	***
	ReadingBottom251	-1.2300	0.0296	< 2e-16	***
γ_{01}	formaldehyde_fall	-0.1175	0.0544	0.0341	*
	globe_temperature_fall	0.0302	0.0349	0.3901	
	globe_temperature_spring	-0.0733	0.0363	0.0485	*
	globe_temperature_winter	0.0725	0.0320	0.0272	*
	pn_2.5_fall	-0.0398	0.0847	0.6398	
	pn_2.5_spring	-0.0622	0.0734	0.3993	
	pn_2.5_winter	0.1754	0.0694	0.0136	*
	pn_coarse_annual	0.0930	0.0461	0.0474	*
	relative_humidity_annual	-0.1443	0.0683	0.0391	*
	temperature_fall	-0.0859	0.0343	0.0148	*
	temperature_spring	-0.0345	0.0488	0.4813	
	temperature_winter	0.0246	0.0535	0.6473	
	ventilation_fall	-0.1885	0.0767	0.0166	*
	ventilation_spring	0.0348	0.0467	0.4591	
	ventilation_winter	0.1183	0.0713	0.1037	
	carbon_monoxide_annual	0.0773	0.0540	0.1566	
	nitrogen_dioxide_annual	-0.0044	0.0398	0.9122	
	Ozone_indoor_annual	0.1208	0.0638	0.0644	.
	TVOC_annual	-0.1217	0.0491	0.0156	*
	velocity_fall	0.0713	0.0452	0.1194	
	velocity_spring	0.0469	0.0533	0.3817	
	velocity_winter	-0.1502	0.0633	0.0210	*
γ_{11}	ReadingTop251: temperature_fall	-0.1184	0.0407	0.0037	**
	ReadingTop251: ventilation_fall	0.1332	0.0308	0.0000	***
	ReadingBottom251: nitrogen_dioxide_annual	0.0782	0.0279	0.0051	**
	English_Learners1: velocity_winter	0.1364	0.0456	0.0028	**

4.6.1.2. Mathematics Scores

According to table 16 in the model for elementary schools' mathematics scores, classroom system type, globe temperature in spring and winter are significant variables. In this model classroom level was used as the random effect and the Akaike information criterion (AIC) is equal to 1899. According to appendix C, comapring to the model without performance variables (with AIC = 4018.2) the model with performance variables has a lower AIC, and therefore is selected as the final model.

Holding all other variables constant, classrooms with single-zone systems have a lower average mathematics score. A lower globe temperature in spring is associated with higher mathematics scores (p-value < 0.05) while a higher globe temperature in winter is associated with higher mathematics scores for elementary students.

There is an interaction effect between globe temperature in fall and high-performer students for mathematics. A lower globe temperature in fall has a greater positive association with high-performer students in mathematics. Positive interaction effects between fine particles in winter, annual ozone concentration, and high-performer students were found. There is also a positive interaction between English learners and fine particles in spring for mathematics scores.

Table 16. Elementary Schools (Mathematics Scores)

Model Inputs	Input Variables	Estimate	Standard Error	p-value	Significance level
γ_{00}	(Intercept)	0.4316	0.1391	0.0056	**
γ_{10}	system_typeSingle-Zone	-0.3820	0.1533	0.0177	*
	Gender1	-0.0436	0.0228	0.0559	.
	Free_Reduced_lunch1	-0.1072	0.0314	0.0007	***
	White_notWhite1	-0.0059	0.0399	0.8832	
	English_Learners1	-0.1350	0.0547	0.0136	*
	MathTop251	1.0900	0.0283	< 2e-16	***
	MathBottom251	-1.2710	0.0278	< 2e-16	***
γ_{01}	formaldehyde_fall	0.0089	0.0550	0.8726	
	globe_temperature_fall	0.0646	0.0378	0.0921	.
	globe_temperature_spring	-0.0917	0.0400	0.0266	*
	globe_temperature_winter	0.1145	0.0348	0.0017	**
	pn_2.5_fall	0.0732	0.0877	0.4067	
	pn_2.5_spring	-0.0104	0.0728	0.8875	
	pn_2.5_winter	-0.0543	0.0719	0.4525	
	pn_coarse_annual	0.0475	0.0464	0.3097	
	relative_humidity_annual	-0.0555	0.0658	0.4030	
	temperature_fall	-0.0443	0.0367	0.2318	
	temperature_spring	0.0556	0.0519	0.2878	
	temperature_winter	-0.0163	0.0545	0.7655	
	ventilation_fall	-0.0722	0.0748	0.3397	
	ventilation_spring	-0.0135	0.0478	0.7784	
	ventilation_winter	0.0116	0.0672	0.8645	
	carbon_monoxide_annual	0.0526	0.0564	0.3544	
	nitrogen_dioxide_annual	0.0013	0.0415	0.9752	
	Ozone_indoor_annual	-0.0353	0.0602	0.5627	
	TVOC_annual	0.0134	0.0500	0.7898	
	velocity_fall	-0.0081	0.0475	0.8648	
	velocity_spring	0.0921	0.0527	0.0867	.
	velocity_winter	0.0413	0.0688	0.5513	
γ_{11}	MathTop251: globe_temperature_fall	-0.0763	0.0270	0.0048	**
	MathTop251: pn_2.5_winter	0.1014	0.0293	0.0006	***
	MathTop251: Ozone_indoor_annual	0.0996	0.0270	0.0002	***
	English_Learners1: pn_2.5_spring	0.0824	0.0384	0.0322	*

4.6.2. Middle/ High Schools

4.6.2.1. Reading Scores

According to table 17 in the model for middle/ high schools' reading scores system type, formaldehyde in fall, globe temperature in spring and winter, fine particles in spring, the temperature in all three seasons (fall, winter, spring), ventilation rate in winter, annual NO2 and ozone concentration are significant variables. In this model school level was used as the random effect and the Akaike information criterion (AIC) is equal to 2032.4. According to appendix C, comapring to the model without performance variables (with AIC = 4564.3) the model with performance variables has a lower AIC, and therefore is selected as the final model.

Holding all other variables constant, classrooms with single-zone systems have a higher average reading score. Lower globe temperature in winter is associated with higher reading scores (p-value < 0.05). A lower formaldehyde concentration in the fall and a lower annual indoor ozone concentration in classrooms are associated with higher reading scores. There is also a positive association between classroom air temperature in spring and a negative association between classrooms' air temperature in winter.

There are interaction effects between demographic and performance variables with IAQ, TC variables for reading scores. While holding all other variables constant, a lower temperature in fall has a greater positive association with reading scores for high-performer students. A lower globe temperature and air velocity in spring have a greater positive association with reading scores for low-performer students. As the number of free-reduced lunch students in classrooms increases, a higher ventilation rate in winter

Table 17. Middle/ High Schools (Reading Scores)

Model Inputs	Input Variables	Estimate	Standard Error	p-value	Significance level
γ_{00}	(Intercept)	-6.7720	2.0060	0.0342	*
γ_{10}	system_typeSingle-Zone	10.1800	3.1200	0.0388	*
	Gender1	0.0050	0.0211	0.8125	
	Free_Reduced_lunch1	-0.0793	0.0269	0.0032	**
	White_notWhite1	0.0582	0.0332	0.0800	.
	English_Learners1	0.0429	0.0485	0.3766	
	ReadingTop25	1.0850	0.0270	< 2e-16	***
	ReadingBottom25	-1.3450	0.0257	< 2e-16	***
γ_{01}	formaldehyde_fall	-1.8620	0.5831	0.0409	*
	globe_temperature_fall	-0.1048	0.4580	0.8342	
	globe_temperature_spring	-0.8882	0.1570	0.0039	**
	globe_temperature_winter	-0.9357	0.1777	0.0054	**
	pn_2.5_fall	-1.3350	0.6564	0.1303	
	pn_2.5_spring	4.4510	0.9913	0.0141	*
	pn_2.5_winter	-0.1729	1.2690	0.9006	
	pn_coarse_annual	0.3633	0.4547	0.4833	
	relative_humidity_annual	-2.3050	0.8733	0.0724	.
	temperature_fall	-1.9280	0.4367	0.0110	*
	temperature_spring	0.6948	0.1758	0.0076	**
	temperature_winter	-0.6148	0.1772	0.0198	*
	ventilation_fall	0.3207	0.1995	0.1998	
	ventilation_spring	0.6564	1.2830	0.6454	
	ventilation_winter	-0.5024	0.1335	0.0042	**
	carbon_monoxide_annual	0.8967	0.5320	0.1865	
	nitrogen_dioxide_annual	-2.2520	0.5384	0.0194	*
	Ozone_indoor_annual	-0.7361	0.1785	0.0149	*
	TVOC_annual	-0.0445	0.6529	0.9500	
	velocity_fall	-0.3901	0.4259	0.4261	
	velocity_spring	-0.2235	0.4759	0.6706	
	velocity_winter	-0.4789	0.2914	0.1840	
γ_{11}	ReadingTop25: pn_2.5_spring	-0.0909	0.0436	0.0371	*
	ReadingTop25: temperature_fall	-0.0543	0.0256	0.0342	*
	ReadingTop25: nitrogen_dioxide_annual	0.1540	0.0361	0.0000	***
	ReadingTop25: TVOC_annual	0.0726	0.0262	0.0056	**
	ReadingTop25: velocity_spring	-0.1084	0.0308	0.0004	***
	ReadingBottom25: globe_temperature_spring	-0.0606	0.0245	0.0136	*
	ReadingBottom25: pn_2.5_spring	-0.1114	0.0258	0.0000	***
	Free_Reduced_lunch1: pn_2.5_spring	-0.0797	0.0237	0.0008	***
	Free_Reduced_lunch1: ventilation_winter	0.0765	0.0272	0.0049	**

has a greater positive association with reading scores. A lower fine particle concentration in spring has a greater positive association with reading scores for high-performer students, low-performer students, and free-reduced lunch students in classrooms. There are also positive interaction effects between high-performer students with annual NO_2 and TVOC concentration.

4.6.2.2. Mathematics Scores

According to table 18 in the model for middle/ high schools' mathematics scores system type, globe temperature in fall and winter, fine particles in fall, the temperature in fall, ventilation rate in spring, annual TVOC, and ozone concentration are significant variables. . In this model school level was used as the random effect and the Akaike information criterion (AIC) is equal to 1769.6. According to appendix C, comapring to the model without performance variables (with AIC = 3877.6) the model with performance variables has a lower AIC, and therefore is selected as the final model.

Holding all other variables constant, classrooms with single-zone systems have a higher average mathematics score. Lower globe temperature in fall (cooling season) is associated with higher reading scores (p-value < 0.05). A lower fine particle concentration in fall is associated with higher mathematics scores. A higher ventilation rate in spring is associated with higher mathematics scores and a higher temperature in fall (cooling season) is associated with higher mathematics scores. There are also positive interactions between annual ozone concentration, annual TVOC concentration, and mathematics scores.

Table 18. Middle/ High Schools (Mathematics Scores)

Model Inputs	Input Variables	Estimate	Standard Error	p-value	Significance level
γ_{00}	(Intercept)	-4.2320	0.7864	0.0000	***
γ_{10}	system_typeSingle-Zone	6.9260	1.2660	0.0000	***
	Gender1	0.0005	0.0235	0.9823	
	Free_Reduced_lunch1	-0.0868	0.0289	0.0027	**
	White_notWhite1	0.0159	0.0379	0.6746	
	English_Learners1	0.0163	0.0546	0.7650	
	MathTop25	1.1010	0.0292	< 2e-16	***
	MathBottom25	-1.3090	0.0292	< 2e-16	***
γ_{01}	formaldehyde_fall	1.4480	0.9857	0.1421	
	globe_temperature_fall	-0.2113	0.0731	0.0039	**
	globe_temperature_spring	0.4018	0.4870	0.4095	
	globe_temperature_winter	0.7978	0.9265	0.3893	
	pn_2.5_fall	-1.8820	0.2099	< 2e-16	***
	pn_2.5_spring	0.8957	0.6298	0.1552	
	pn_2.5_winter	-2.1120	1.3460	0.1167	
	pn_coarse_annual	1.5630	0.9932	0.1157	
	relative_humidity_annual	-1.3030	1.5630	0.4047	
	temperature_fall	0.4453	0.2018	0.0275	*
	temperature_spring	-1.0620	0.9344	0.2559	
	temperature_winter	-0.1537	0.5435	0.7774	
	ventilation_fall	-0.9732	1.2480	0.4357	
	ventilation_spring	1.4280	0.4715	0.0025	**
	ventilation_winter	0.5663	0.6264	0.3661	
	carbon_monoxide_annual	-0.0168	0.0967	0.8619	
	nitrogen_dioxide_annual	0.8543	0.9673	0.3773	
	Ozone_indoor_annual	0.4391	0.2164	0.0426	*
	TVOC_annual	1.6300	0.7069	0.0213	*
	velocity_fall	-0.6429	0.3587	0.0733	.
	velocity_spring	-0.6810	0.4950	0.1692	
	velocity_winter	-0.0114	0.6601	0.9863	
γ_{11}	MathTop25: temperature_winter	-0.0619	0.0288	0.0316	*
	MathTop25: TVOC_annual	0.0905	0.0288	0.0017	**
	MathBottom25: Ozone_indoor_annual	-0.0660	0.0276	0.0170	*
	Free_Reduced_lunch1: ventilation_winter	0.0725	0.0258	0.0050	**
	English_Learners1: velocity_winter	-0.1156	0.0420	0.0060	**

There are interaction effects between demographic and performance variables with IAQ, TC variables for mathematics scores. As the number of free-reduced lunch students in classrooms increases, a higher ventilation rate in winter has a greater positive association with mathematics scores, while holding all other variables constant. As the number of English learner students in classrooms increases, a lower air velocity in winter has a greater positive association with mathematics scores. A lower classroom temperature in winter has a greater positive association with mathematics scores for high-performer students. There are also positive interaction effects between annual TVOC and ozone concentration with high-performer students for mathematics scores.

4.7. Discussion (Research Question 3)

In this research question the assoctioans between IAQ, thermal environmental factors and student academic performance was addressed. A HLM model was used explore the association and potential interactions withstudents' demographic data. A linear model is less complex and can be more interpreteable. Comparing to a non-linear model can give a more general result which can be applied to other samples, however a non-linear model may give a better fit on this model.

For each IAQ and thermal environment variable the results is discussed in the next section.

4.7.1. Mechanical Systems

Potential impacts on student learning outcomes should be considered when selecting mechanical system types for school environments. From this study, the type of mechanical system used for ventilation has an association with elementary students' mathematics scores and middle/ high schools' mathematics and reading scores. Elementary school classrooms with a single-zone system were estimated to have lower mathematics scores when compared to classrooms with multi-zone systems. Figure 27 shows the range of students' scores in different elementary classrooms for each mechanical system type. From additional studies by this research team, single-zone systems (classrooms with unit ventilator) were found to be associated with higher coarse particle counts, lower ventilation rates, and higher levels of background noise (Lau et al., 2020). Another independent study in Danish schools indicated that balanced mechanical ventilation or mechanical exhaust (compared to classrooms without mechanical systems) is associated with higher student grades (Toftum et al., 2015).

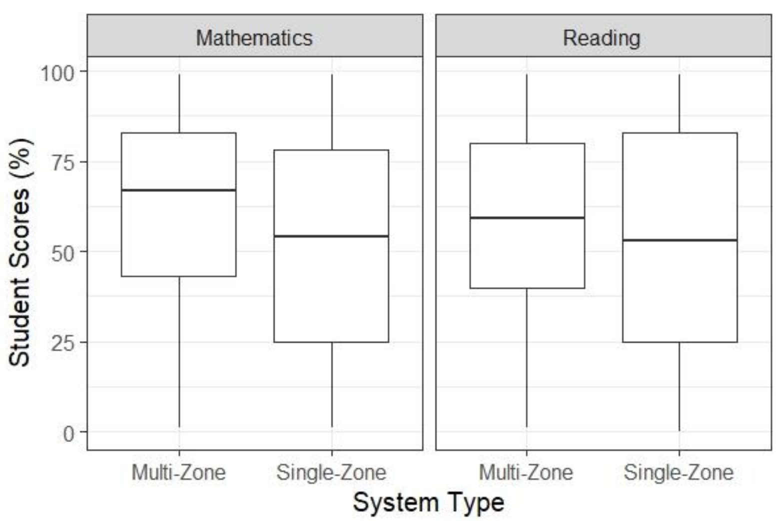


Figure 27. The range of **elementary** students math and reading scores for each mechanical system type

In general, multi-zone systems provide a greater capacity to deliver fresh air and use higher performance filtration to improve indoor air quality, however in middle/ high school classrooms with single-zone systems higher math and reading scores (comparing to classrooms with multi-zone systems) was observed. Figure 28 shows the range of students' mathematics and reading scores in middle/ high school classrooms with different mechanical systems. In middle/ high schools students don't stay in the same room during the school day, therefore their scores might be associated with the environmental condition of all classrooms they attend and may increase the impact of confounding factors on the results of the study. More experimental studies in classrooms with a controlled environment serving by different types of mechanical systems may help to investigate the impact of system selections on students' scores.

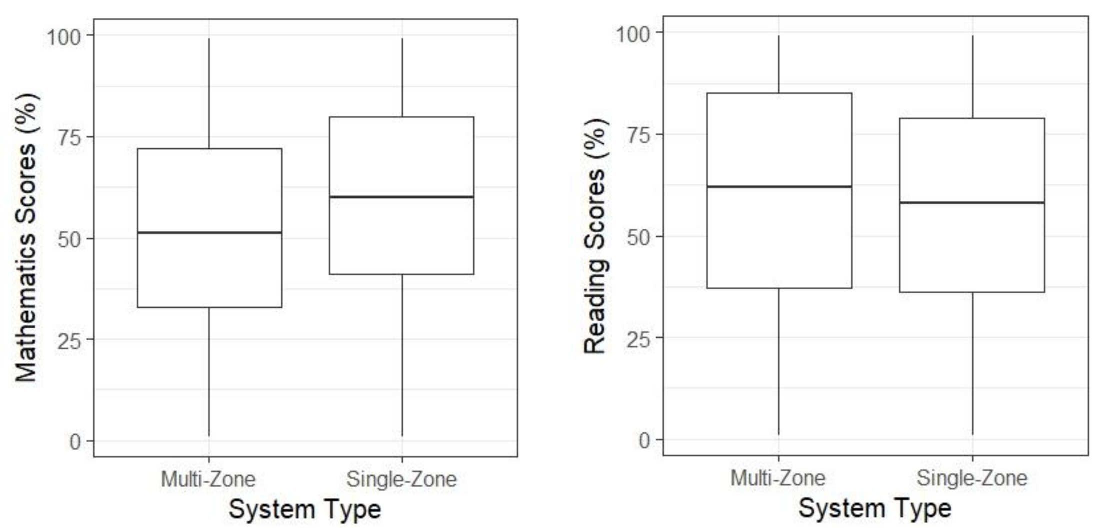


Figure 28. The range of **middle/ high** school students mathematics and reading scores for each mechanical system type

4.7.2. Ventilation Rates

In this study associations between ventilation rates in all three seasons (fall, winter, spring) and students' scores, as well as interactions with demographic and performance variables, were found. In previous literature, ventilation rates were found to be associated with student learning and test performance. Mendell et al. collected data from 150 classrooms in California and found a potential positive association between classroom ventilation rate and learning (Mendell et al., 2016). Haverinen-Shaughnessy et al. concluded in multiple studies that there might be an association between classroom ventilation rates and student performance. (U. Haverinen-Shaughnessy et al., 2011b; Ulla Haverinen-Shaughnessy et al., 2015).

In elementary schools, ventilation rate in fall was found statistically significant for reading scores while interacting with high-performer students. According to one study in the Southwestern US (Ulla Haverinen-Shaughnessy et al., 2015) significant correlations were observed between the percentage of students scoring satisfactorily in mathematics or reading and ventilation rates. To the best of authors' knowledge no prior study investigates the interaction effect between high-performer students and ventilation rates and more experimental studies are needed to confirm the interactions found in this study. No association between ventilation rates in spring or winter and students' scores was found. Figure 29 shows ventilation rate ranges in three seasons for elementary schools. Seasonal variation was found in the ventilation rates of the classrooms with rates in winter significantly lower than those in fall and spring in the same classrooms (Kabirikopaei &

Lau, 2020). It is possible that there is not enough variation across elementary classrooms regarding winter and spring ventilation rates to discover any associations.

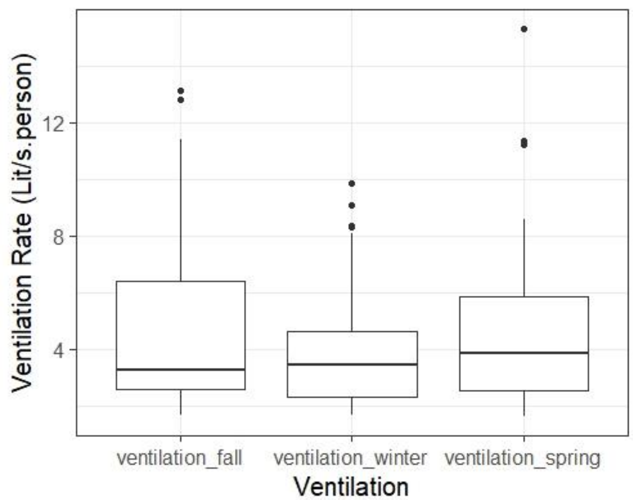


Figure 29. Ventilation rate range in elementary classrooms in different seasons

In middle/ high schools, ventilation rate in winter and spring was found statistically significant for reading and mathematics scores, while ventilation rate in winter is interacting with free-reduced lunch students. Figure 30 shows the range of ventilation rates in different seasons in middle/ high schools. The positive association between ventilation rates in spring and middle/ high school students scores is in agreement with (Mendell et al., 2016) and (Ulla Haverinen-Shaughnessy et al., 2015) studies, however, in these studies, observed associations between ventilation rates and student scores were found based on samples from elementary schools. The results of this study show that there are positive associations between ventilation rates and high school students' scores as well. Higher ventilation rates may lead to the removal of contaminants in classrooms and may help students to have a better performance in classrooms.

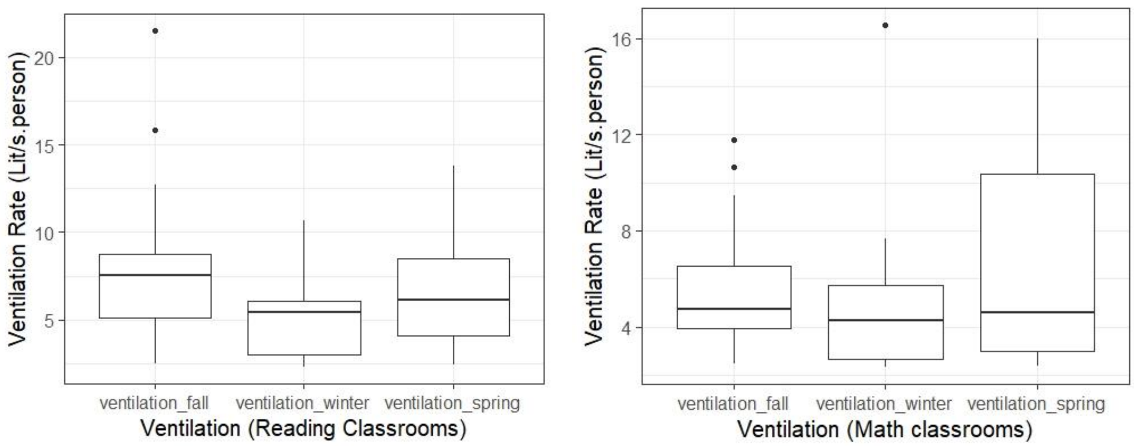


Figure 30. The range of ventilation rates in three seasons in middle/ high schools

In middle/ high schools, positive interaction between ventilation rate in winter and the number of free- reduced lunch students in classrooms were found. Figure 31 shows the range of free- reduced lunch students' scores compared to other students. free- reduced lunch students (students from lower-income families) have lower mathematics and reading scores and according to the results of this study, their scores might be associated with ventilation rates. In the study performed by (Ulla Haverinen-Shaughnessy et al., 2015) no association between ventilation rates and the number free-reduced lunch students in classrooms was found. More experimental studies are needed to confirm the impact of ventilation rates on students from lower-income families.

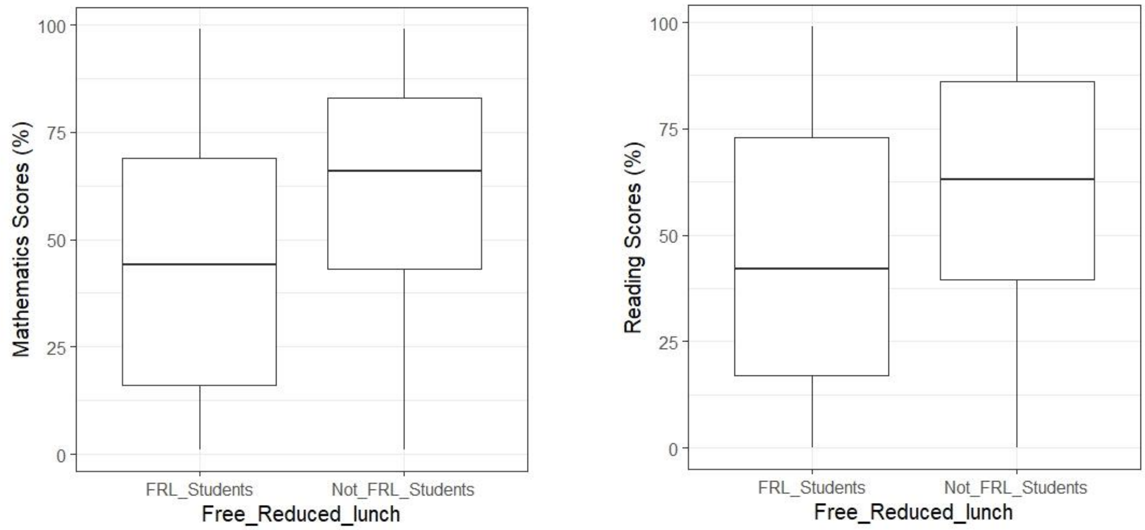


Figure 31. Range of free-reduced lunch (FRL) students scores comparing to other students

The interactions found between seasonal ventilation rates and the demographic variable (free-reduced lunch) reveal the importance of student demographics when interpreting the effects of IAQ factors in classrooms on student outcomes. As presented in previous studies, different demographic groups respond to the indoor environmental factors differently (Ronsse & Wang, 2013), and, as the percentage of students from one demographic group changes in the classroom, the relationships between ventilation and performance might be affected. The interaction between ventilation rate and high-performer students also shows that ventilation rate may influence one group of students. Therefore, performing student-level experimental studies on subjects from different demographic groups in IAQ studies in classrooms will help identify the impacts related to student socio-economic conditions.

4.7.3. Particles

Fine particle counts were considered as three input variables for each of the three seasons studied; however, coarse particle counts were processed as a single variable (average of three seasons) in the model.

In elementary schools, fine particles in winter are positively associated with reading scores and fine particles in spring have a positive interaction with English learner students for mathematics scores. There is also a positive association between coarse particles and elementary school reading scores. More research is needed to explain the positive relationship between particle concentration and student scores and explore the potential confounding factors that may explain this relationship. For example, student outcomes are positively affected by “active” learning experiences, but, at the same time, those activities increase airborne particle concentrations. Student activity highly influenced the re-suspension of particles in classrooms, especially when ventilation rates were inadequate (Almeida et al., 2011). Also, educational activities such as hands-on learning in classrooms may be a significant source of indoor particles (Polednik, 2013).

In middle/ high schools fine particles in spring have negative interactions with high-performers, low-performers, and free-reduced lunch students for reading scores. There is also a negative association between fine particles in fall and mathematics scores for middle/ high schools. According to the one study which directly studied the effects of particles on students’ performance, the reduction of classrooms’ airborne particles doesn’t have any expected short-term benefit on students’ performance (Wargocki et al., 2008); however, in their model, it shows that there is a negative relationship between fine particles and students’ scores which is in agreement with the results of this study in middle/ high schools.

Classroom occupancy density and location of the school may also be important factors in the concentration of particles in a classroom. Highly dense classrooms in more polluted areas are subject to more particle concentrations in classrooms. To control particle concentrations in classrooms, appropriate ventilation systems and high-efficiency filters should be used in school buildings.

4.7.4. Temperature

Associations between classrooms’ temperature in all three seasons and students' scores were found. In elementary schools, there is a negative interaction between classrooms’ air temperature in fall and high-performer students. Regarding the fact that in the measured classrooms mechanical systems were still working in cooling mode during fall, a lower temperature may be associated with higher student scores. This association is in agreement with the previous literature in which a relationship between temperature and students’ performance was found in the cooling season. Wargocki et.al conducted multiple experiments on the relationship between the student’s performance and temperature and concluded that reduced temperature in summer has a positive impact on students’ performance (Wargocki & Wyon, 2007). According to Figure 32 classrooms’ air temperature in elementary schools varies in a limited range in different seasons. Maybe there are not enough variations in the temperature of classrooms in spring and winter to discover the potential associations between temperature and students’ scores.

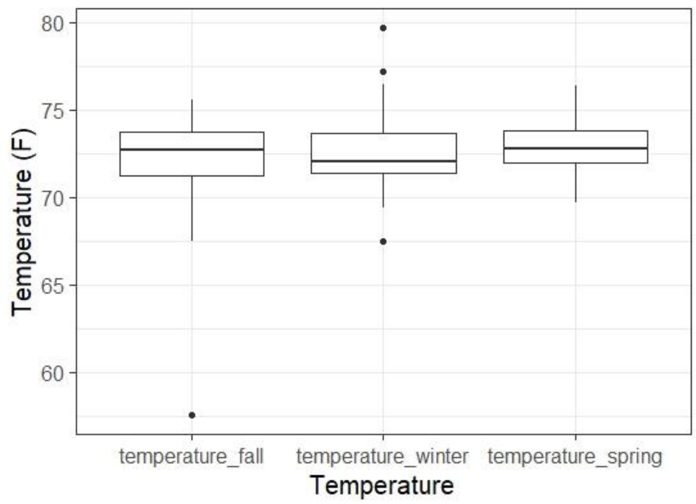


Figure 32. Classrooms air temperature range in elementary classrooms in different seasons

In middle/ high schools there is a negative association between classrooms' temperature in winter and reading scores. Confounding factors like students' clothing might be the reason for this negative association between classroom temperature in winter and students' reading scores. The negative interaction between temperature in fall and high-performers in reading in middle/ high schools is in agreement with the association observed in elementary schools. A preference for lower temperature in fall (cooling season) may be explained by better thermal comfort and associated to increased student's scores. In middle/ high schools, a positive association between temperature in fall and mathematics scores as well as a negative interaction between temperature in winter and high-performer students was found. The positive association between temperature in fall (during the cooling season) and the negative interaction for temperature in winter (during the heating season) may be associated with cofounding factors in classrooms.

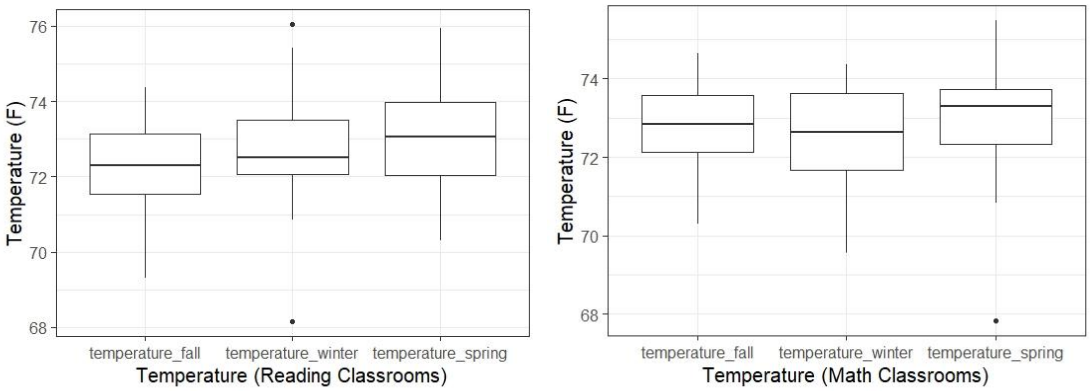


Figure 33. Classrooms air temperature range in middle/ high schools in different seasons

Based on the author's knowledge most of the previous studies have been performed in the cooling season and the impact of cooling on student's scores has been investigated. The results of this study show reducing the temperature during the cooling season (fall) can help to improve student's performance. The relationship may also be explained by the occupant's thermal comfort preference during different seasons. Occupants prefer a cooler indoor temperature than in the winter. The decreasing temperature within an optimal range can have a positive association with students' performance, however, overcooling in classrooms (indoor temperature beyond the observed temperature range) can increase energy consumption and reduces students' comfort. Using a control strategy to maintain the classroom's temperature in the comfort range is necessary for all mechanically ventilated classrooms. According to the results of this study, in the statistical models, air temperatures were not associated with mathematics and reading scores in all three seasons. Since all the classrooms in the sample are mechanically ventilated, a much smaller variance in temperatures may lead to the insignificance results in a specific season. More experiments in the seasonal context are needed to confirm the effect of temperature on student's performance under different seasons.

Based on the author's knowledge there is no study in which the impact of classrooms' temperature on minority groups, high-performers, and low-performers has been investigated. More experimental studies are needed to discover the impact of temperature on the scores of students within different socioeconomic backgrounds.

4.7.5. Globe Temperature

Classroom's globe temperature in all three seasons has an association with student's reading and mathematics scores. In elementary schools, a negative association in spring and a positive association in winter with both mathematics and reading scores were found. In addition to these associations, a negative interaction between globe temperature in fall and high-performers for mathematics scores was found. Figure 34 shows the range of globe temperature in elementary schools in different seasons. Globe temperature is a measurement of radiation heat effect in addition to sensible heat as measured by dry-bulb temperature, therefore negative associations in spring (cooling season) and positive associations in winter (heating season) may improve students' thermal comfort in classrooms and potentially may lead to higher scores.

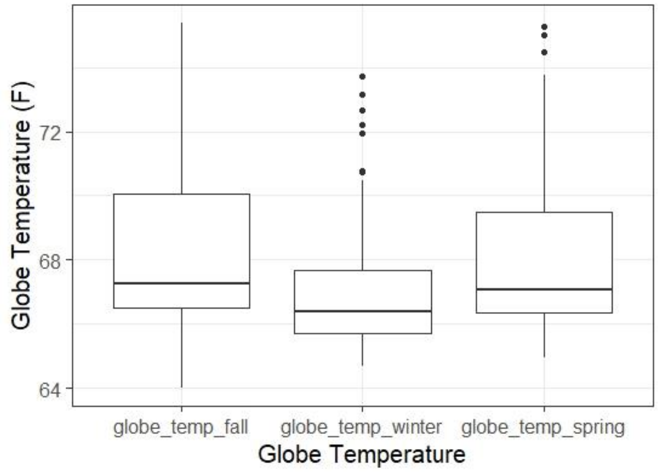


Figure 34. Classrooms globe temperature range in elementary schools in different seasons

In middle/ high schools, a negative association between classrooms' globe temperature in winter and students' reading scores was found. Figure 35, shows the range of globe temperature in reading and mathematics classrooms in different seasons. Regarding this fact that classrooms' temperature in winter in middle/ high schools have also a negative association with students reading scores, maybe confounding factors (e.g. students' clothing in winter) causes this association in the model. This reduction in thermal comfort may potentially be associated with lower reading scores in middle/ high schools. There is also a negative interaction between globe temperature in spring and low-performer students for reading scores as well as a negative association between globe temperature in fall and mathematics scores in middle/ high schools. Direct sunlight or hot surfaces may elevate classroom globe temperature in spring and may be associated with lower scores for students.

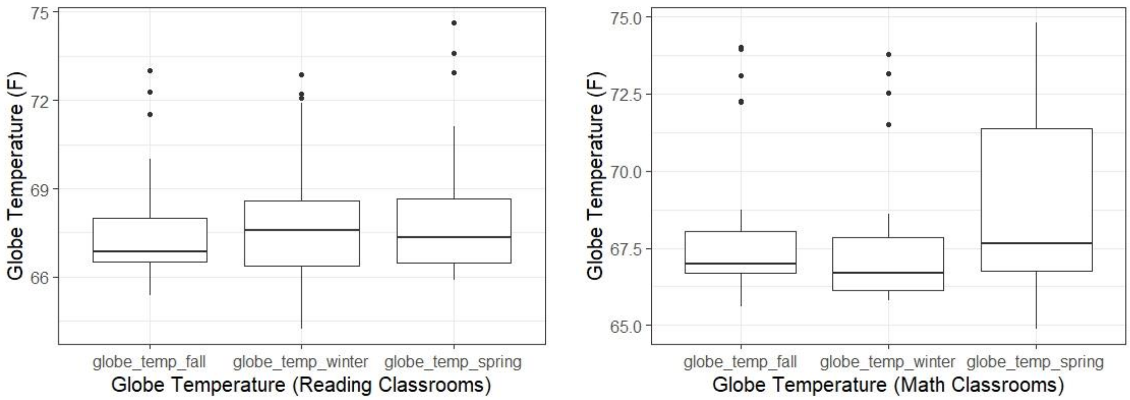


Figure 35. Classrooms globe temperature range in middle/ high schools in different seasons

Avoiding direct sunlight and hot surfaces in classrooms during the cooling season can help to reduce the globe temperature, while in the heating season hot surfaces may help to elevate classrooms globe temperature. No previous literature specifically on the impact of globe temperature on student's performance was found by the authors. Comparing to temperature, globe temperature could be a better indicator of the classroom's thermal environment, since it included dry-bulb temperature, mean radiant temperature, and air velocity. More experimental studies are needed to confirm the impact of globe temperature on student's performance in classrooms.

4.7.6. Air Velocity

Classroom' indoor air velocity in winter and spring is associated with students' scores. In elementary schools a positive interaction effect between classrooms' air velocity and English Language learner students was found. Figure 36 shows the range of air velocity in elementary classrooms. In elementary school classrooms, air velocity in winter has a lower range comparing to other seasons, however, air velocity in winter (main effect) has a negative association with reading scores. The positive interaction between air velocity in winter and English learner students shows that decreasing air velocity in classrooms may have less association with higher reading scores for English learner students. Reading scores for English learner students (students from mostly immigrant families) may be impacted less by environmental factors and other non-environmental factors (ex. Social, family, …) may have more impact to improve their scores.

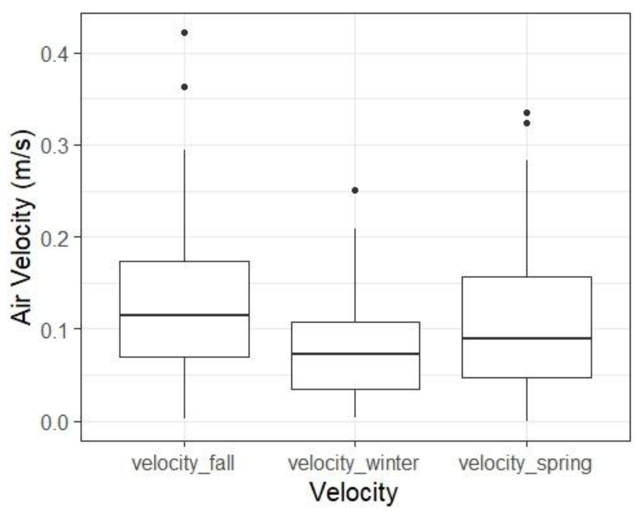


Figure 36. Classrooms air velocity range in elementary schools in different seasons

In middle/ high schools a negative interaction for reading scores between air velocity in spring and high-performer students was found. According to figure 37 shows the range of air velocity in middle/ high schools’ reading and matheamtcis classrooms. The negative interaction between air velocity in winter and English learner students' mathematics scores may be due to the high air velocity range in mathematics classrooms (Figure 36)

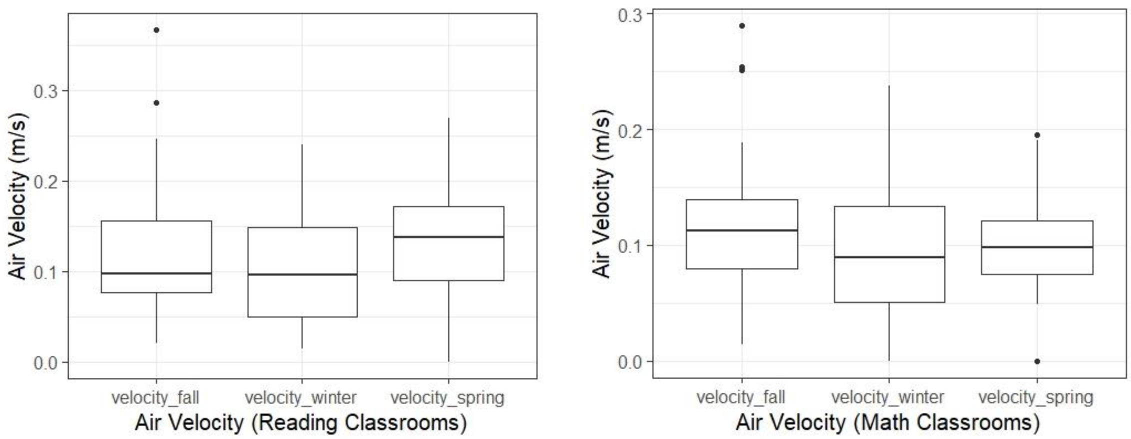


Figure 37. Classrooms air velocity range in middle/ high schools in different seasons

Air velocity is mostly driven by the classroom’s mechanical systems and air distribution in the space. Figure 38 shows the range of air velocity in classrooms with different mechanical systems during different seasons. According to this figure air velocity in classrooms with multi-zone systems changes in a lower range compared to single-zone systems. This can be the result of controlling strategies in multizone and more consistent air distribution in multizone systems. In most of the previous literature, the relationship between classroom ventilation rate and student’s performance is studied and the air velocity is disregarded. The results of this study show that the classroom’s air velocity has associations with students’ performance. High variance in air velocity measurements in a classroom may be associated with a poor air distribution in the space and the stagnant zones caused by poor air distribution reveals a lower fresh air in the zone which may affect student’s learning performance.

Air velocity measurements took place in unoccupied time. Budget limitations, expensive air velocity sensors, and the distractions that air velocity sensors may cause for students during the occupied time are the main reasons that lead the research to conduct air velocity measurements during the unoccupied time. The unoccupied measurements were carried out within the first hour of the student's dismissal while the mechanical system was still on. Air velocity sensors were placed in a location at the center of classrooms and three air velocity sensors measured the airspeed in three levels. The research team believes that air velocity measurements in three levels can give an appropriate estimation of the velocity of air in classrooms, however more experimental studies in a controlled chamber are needed to confirm the associations reported in this study.

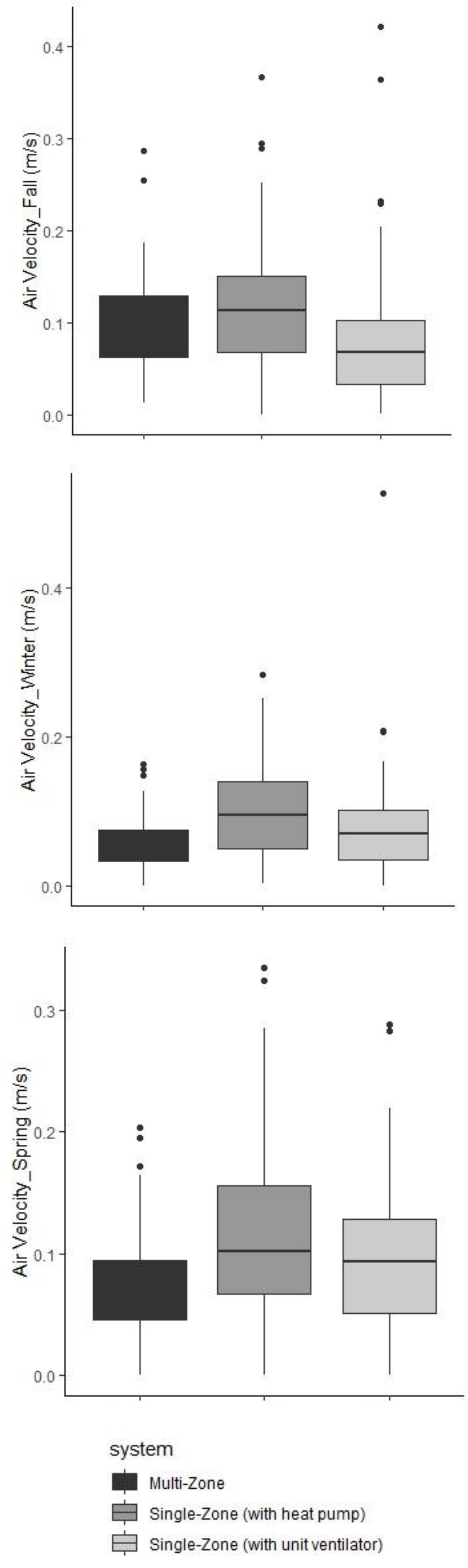


Figure 38. The range of air velocity in classrooms

4.7.7. Relative Humidity, water damage, odor, and mold

Table 19 summarizes the number of classrooms identified with odor, damage (stain), and mold in each season. There is no sign of visual mold was observed in the studied classrooms, which is explained by the fact that relative humidity in these classrooms is not in an elevated range (i.e. > 60% RH). There are damage (stain) signs were found in classrooms ceilings which may be due to the water dripping from HVAC piping systems. Regular maintenance check-ups of the school's mechanical systems can help to avoid damage to the classroom's ceilings or the locations exposed to water dripping.

Table 19. Number of classrooms identified with damage(stain), mold, and odor in each season

		Number of classrooms identified (sample size: 220)
Odor	Fall	3
	Winter	3
	Spring	11
Damage (stain)	Fall	51
	Winter	50
	Spring	42
Mold	Fall	0
	Winter	0
	Spring	0

In this study, only one negative association between annual relative humidity and elementary students' reading scores was found. No association between relative humidity and student's scores in middle/ high schools and elementary mathematics scores was found. This confirms the results of a previous study in which no association between relative humidity and student performance is reported (Ulla Haverinen-Shaughnessy et al., 2015). All classrooms in the sample located in one climatic region and were mechanically ventilated, therefore the variance of relative humidity in the statistical model may not be high enough to show the significance of the association. There is a limited number of studies in which the impacts of relative humidity on student's performance are explored.

4.7.8. Other factors from the unoccupied measurements

Ozone (O_3) concentration was found to have statistically significant relationships with middle/ high school students' reading and mathematics scores; however, more experimental studies are needed to confirm this relationship. Ozone mainly originates outdoors, but classroom indoor O_3 concentration might influence student outcomes due to a large amount of exposure time. In this study, O_3 concentration was measured for 10-15 minutes only in unoccupied classrooms~~,~~ since the measurement device was too loud to be on during school. It is expected that O_3 concentrations during occupied times would be lower than the values measured during unoccupied times because occupants remove more O_3 than furniture and surfaces do (Andreas Fischer et al., 2013). Therefore, elevated O_3 values may be the reason for their significance in the statistical model.

During the unoccupied 10-15 minute measurement periods, CO, TVOC, and NO_2 concentrations in classrooms were also measured, and associations with student performance were found. Continuous measurements in classrooms may help to investigate any impacts of elevated CO, TVOC, or NO_2 levels on student learning. Since all these contaminants are generated from outdoor sources, and both variables were found statistically associated with student performance, more continuous experiments regarding outdoor and classroom CO, TVOC, and NO_2 concentrations and student scores are needed to detect potential impacts of CO, TVOC, and NO_2 concentrations on student learning.

4.7.9. Recommendations for Future Studies

The results of this study can be used to design future experiments focusing on associations between significant IAQ factors and student academic performance. Seasonal variations in the associations examined to reveal the importance of seasonal measurements in IAQ studies. Continuous measurements in different seasons help to investigate trends in seasonal IAQ factors and relationships with student performance. The classrooms measured in this study, all are located in one climate zone. Having classrooms from different climate zones can help to investigate the associations between IAQ, thermal environment and performance of the students from the climate zones with different outdoor condition range. Considering predicted mean vote (PMV) in the study by providing questionnaire for students to vote about their thermal confort condition can help to consider PMV values in the model.

Interactions found between student demographic information and IAQ factors indicate the importance of considering demographic data in school indoor environmental studies. Controlled experiments will also allow statements of causality to be made. In future experiments it is important to select subjects from different students' demographic to be able to control the experiment with students' socioeconomic background. In this study lunch-pay status data were used as the factor to evaluate student's family income. Adding more socioeconomic data to the model help to reduce the confounding factors to find true associations.

Classroom characteristics (such as floor and ceiling types) were not used in the statistical model, because the research team did not find enough variations in the current sample to warrant further study. In future studies selecting classrooms with more variety in furniture and indoor materials for walls and ceilings can help to find any potential associations between classrooms' indoor materials and students' performance.

In this study, student level data (demogrphics, scores) and assrooms level date (environmental data) were used for statistical analysis. Adding more levels of data (school level, district level) may help to have a more comprehensive study which can help to reduce the effect of confounding factors in the model. Even though the performance varible was created based on classrooms level, it still had a high level of significance with the response variables. In future work if other measures (e.g. other students' scores than the ones used as the response) are used, the model performance may improve.

5. Conclusion

Adequate ventilation is important in occupied spaces. From this field study, ventilation rates estimated by three methods varied significantly. These results reveal the importance of selecting the best method for measurements and estimations. Selecting a tracer-gas method without first evaluating the type of ventilation system, occupant demographics and activities, and a detailed layout may lead to inaccurate estimates of ventilation rate. Based on the results of this study, a steady-state method may give the most reliable results with the lowest uncertainty when compared to decay and build-up methods. To decrease the uncertainty in the estimated ventilation rate, improving the accuracy of CO_2 measurements in the field is suggested. A greater certainty for the calculated ventilation rates leads to a better understanding of actual conditions and evaluation of indoor air quality allowing building owners and design engineers to identify opportunities to maximize occupant health and save energy.

According to the results of this study, depending on the schools' mechanicanical systems, measuremments of IAQ factors in schools can perform in school level or classroom level. More measurements in a specific school (in different classrooms) may lead to more samples but it may not be always necessary and the research team's resources can devote to measurements in more different schools. Based on the results of this study in the schools with multi-zone systems, fewer measurements for CO_2 concentrations, coarse particles, and air velocity measurements may be sufficient to represent the entire condition of the schools.

Finally, this large-scale study examined associations between indoor air quality, thermal environmental factors, and student performance in K-12 classrooms in the Midwestern US. Mechanical system types and adequate ventilation rates play a significant role in classroom indoor air quality, and these factors show significant associations with student learning outcomes. In this study seasonal ventilation rates in classrooms are the most significant IAQ factor that may be associated with students' scores. Ventilation rate in fall was found significant for elementary schools while it has a positive interaction with high performer elementary students. In middle/ high schools higher ventilation in winter has a positive association with free-reduce lunch students scores. Ventilation rate is one of major IAQ factors that shows significant associations with students' performance in multiple studies. Adequate ventilation rates and efficient filters help to reduce contaminants in classrooms and potentially improve student performance. The seasonal globe temperature and air velocity are the most significant thermal environmental factors that may impact the student's performance. The relationship may also be explained by the occupant's preference during different seasons. Occupants prefer a warmer indoor temperature than in the summer. . Appropriate air distribution and mechanical system selection are important to avoid extremely high air velocity that produces discomfort draft.

The relationship between students' test scores and their potential interactions with different demographic groups was investigated with student-level data and using a multi-level model. The results show that IAQ and thermal conditions of classrooms were associated with academic performance when controlled by demographic groups (gender, ethnicity, lunch-pay status, and English language learner). For example in middle/ high schools, higher ventilation rates in winter and lower fine particles in spring have a positive interaction with free-reduced lunch students scores. Designers and engineers may consider a higher rate of ventilation and higher efficiency filters in classrooms with a greater number of free- reduced lunch students, however more experimental studies are needed to support this recommendation. The interaction effects between IAQ, TC factors, demographic and performance variables show that students may not benefit similarly from the changes in classrooms' indoor environment. Future experiments on the relationship between ventilation rate and students' performance may consider student's demographics in the study. The interactions between IAQ, TC factors, and students' performance groups reveal the importance of student-level studies, which helps to group students based on demographics and performance levels.

This research will provide information to school districts and design engineers who are interested in improving the school environment for better student performance. The results of this study can be adopted to design experiments for causality relationships and to confirm the effects of IAQ, Thermal environment factors on student academic performance. Besides, this study provides valuable insight for school districts, designers, and engineers to improve classroom environments to maximize student academic success.

References

Allen, G., Gold, D. R., Damokosh, A., Serrano, P., Hayes, C., & Castiilejos, M. (1996). Comparison of Outdoor and Classroom Ozone Exposures for School Children in Mexico City. *Journal of the Air and Waste Management Association*, *46*(4), 335–342. https://doi.org/10.1080/10473289.1996.10467468

Allen, J. G., Macnaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2016). *Associations of Cognitive Function Scores with Carbon Dioxide , Ventilation , and Volatile Organic Compound Exposures in Office Workers : A Controlled Exposure Study of Green and Conventional Office Environments*. *124*(6), 805–812.

Almaghrebi, A., Aljuheshi, F., Rafaie, M., James, K., & Alahmad, M. (2020). Data-driven charging demand prediction at public charging stations using supervised machine learning regression methods. *Energies*, *13*(6). https://doi.org/10.3390/en13164231

Almeida, S. M., Canha, N., Silva, A., Do Carmo Freitas, M., Pegas, P., Alves, C., Evtyugina, M., & Pio, C. A. (2011). Children exposure to atmospheric particles in indoor of Lisbon primary schools. *Atmospheric Environment*, *45*(40), 7594–7599. https://doi.org/10.1016/j.atmosenv.2010.11.052

Alshitawi, M. S., & Awbi, H. B. (2011). Measurement and prediction of the effect of students' activities on airborne particulate concentration in a classroom. *HVAC and R Research*, *17*(4), 446–464. https://doi.org/10.1080/10789669.2011.583708

American Society of Heating, Refrigerating and Air-Conditioning Engineers, I. (2010). *ANSI/ASHRAE Standard 62.1*.

Asif, A., Zeeshan, M., & Jahanzaib, M. (2018). Indoor temperature, relative humidity and CO2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems. *Building and Environment*, *133*(August 2017), 83–90. https://doi.org/10.1016/j.buildenv.2018.01.042

ASTM International. (2018). *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*. https://doi.org/10.1520/D6245-18

ASTM International. (2019). ASTM Standard E741−11, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. In *West Conshohocken, PA* (Vol. 00, Issue ASTM International 0 (Reapproved 2017)). https://doi.org/10.1520/E0741-11R17

Bainbridge, W. L., & Lesley, T. J. (2002). DEMOGRAPHICS, DIVERSITY, AND K-12 ACCOUNTABILITY The Challenge of Closing the Achievement Gap. *Education and Urban Society*, *34*(4), 422–437.

https://doi.org/https://doi.org/10.1177/00124502034004002

Bakó-biró, Z., Clements-croome, D. J., Kochhar, N., Awbi, H. B., & Williams, M. J. (2012). Ventilation rates in schools and pupils ’ performance. *Building and Environment*, *48*, 215–223. https://doi.org/10.1016/j.buildenv.2011.08.018

Bakó-Biró, Z., Clements-Croome, D. J., Kochhar, N., Awbi, H. B., & Williams, M. J. (2012). Ventilation rates in schools and pupils’ performance. *Building and Environment*, *48*(1), 215–223. https://doi.org/10.1016/j.buildenv.2011.08.018

Bali, V. A., & Alvarez, R. M. (2004). The race gap in student achievement scores: Longitudinal evidence from a racially diverse school district. *Policy Studies Journal*, *32*(3), 393–415. https://doi.org/10.1111/j.1541-0072.2004.00072.x

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Batterman, S., Su, F. C., Wald, A., Watkins, F., Godwin, C., & Thun, G. (2017). Ventilation rates in recently constructed U.S. school classrooms. *Indoor Air*, *27*(5), 880–890. https://doi.org/10.1111/ina.12384

Batterman, Stuart. (2017). Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms. *International Journal of Environmental Research and Public Health*, *14*(2), 1–22. https://doi.org/10.3390/ijerph14020145

Ben-David, T., Rackes, A., & Waring, M. S. (2017). Alternative ventilation strategies in U.S. offices: Saving energy while enhancing work performance, reducing absenteeism, and considering outdoor pollutant exposure tradeoffs. *Building and Environment*, *116*, 140–157. https://doi.org/10.1016/j.buildenv.2017.02.004

Bluyssen, P. M., Kim, D. H., Eijkelenboom, A., & Ortiz-Sanchez, M. (2020). Workshop with 335 primary school children in The Netherlands: What is needed to improve the IEQ in their classrooms? *Building and Environment*, *168*(October 2019), 106486. https://doi.org/10.1016/j.buildenv.2019.106486

Bluyssen, P. M., Zhang, D., Kurvers, S., Overtoom, M., & Ortiz-Sanchez, M. (2018). Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings. *Building and Environment*, *138*(April), 106–123. https://doi.org/10.1016/j.buildenv.2018.04.032

Boulic, M., Phipps, R., Ancelet, T., Davy, P. K., Wang, Y., Trompetter, W. J., & Garcia-Ramirez, J. C. (2018). The effect of ventilation on air particulate matter in school classrooms. *Journal of Building Engineering*, *18*(September 2017), 164–171. https://doi.org/10.1016/j.jobe.2018.03.009

Brdarić, D., Kovač-Andrić, E., Šapina, M., Kramarić, K., Lutz, N., Perković, T., & Egorov, A. (2019). Indoor air pollution with benzene, formaldehyde, and nitrogen dioxide in schools in Osijek, Croatia. In *Air Quality, Atmosphere and Health* (Vol. 12, Issue 8). https://doi.org/10.1007/s11869-019-00715-7

Callahan, R. M. (2005). Tracking and high school english learners: Limiting opportunity to learn. *American Educational Research Journal*, *42*(2), 305–328. https://doi.org/10.3102/00028312042002305

Carrion-Matta, A., Kang, C. M., Gaffin, J. M., Hauptman, M., Phipatanakul, W., Koutrakis, P., & Gold, D. R. (2019). Classroom indoor PM2.5 sources and exposures in inner-city schools. *Environment International*, *131*(June), 104968. https://doi.org/10.1016/j.envint.2019.104968

Chan, W. R., Li, X., Singer, B. C., Pistochini, T., Vernon, D., Outcault, S., Sanguinetti, A., & Modera, M. (2020). Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. *Building and Environment*, *167*(September 2019), 106426. https://doi.org/10.1016/j.buildenv.2019.106426

Chauhan, A. J., Inskip, H. M., Linaker, C. H., Smith, S., Schreiber, J., Johnston, S. L., & Holgate, S. T. (2003). Personal exposure to nitrogen dioxide (NO2) and the severity of virus-induced asthma in children. *Lancet*, *361*(9373), 1939–1944. https://doi.org/10.1016/S0140-6736(03)13582-9

Clarkson, L. M. C. (2008). Demographic data and immigrant student achievement. *Theory into Practice*, *47*(1), 20–26. https://doi.org/10.1080/00405840701764698

Claude-Alain, R., & Foradini, F. (2016). Simple and Cheap Air Change Rate Measurement Using CO 2 Concentration Decays . *International Journal of Ventilation*, *1*(1), 39–44. https://doi.org/10.1080/14733315.2002.11683620

Clements-Croome, D. J., Awbi, H. B., Bakó-Biró, Z., Kochhar, N., & Williams, M. (2008). Ventilation rates in schools. *Building and Environment*, *43*(3), 362–367. https://doi.org/10.1016/j.buildenv.2006.03.018

Coley, D. A., & Beisteiner, A. (2016). Carbon Dioxide Levels and Ventilation Rates in Schools. *International Journal of Ventilation*, *1*(1), 45–52. https://doi.org/10.1080/14733315.2002.11683621

Cui, S., Cohen, M., Stabat, P., & Marchio, D. (2015). CO2 tracer gas concentration decay method for measuring air change rate. *Building and Environment*, *84*, 162–169. https://doi.org/10.1016/j.buildenv.2014.11.007

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003). Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. *Indoor Air*, *13*(1), 53–64. https://doi.org/10.1034/j.1600-0668.2003.00153.x

Demirel, G., Özden, Ö., Döğeroğlu, T., & Gaga, E. O. (2014). Personal exposure of primary school children to BTEX, NO2 and ozone in Eskişehir, Turkey: Relationship with indoor/outdoor concentrations and risk assessment. *Science of the*

Total Environment, *473–474*(2), 537–548. https://doi.org/10.1016/j.scitotenv.2013.12.034

Deng, S., & Lau, J. (2019). Seasonal variations of indoor air quality and thermal conditions and their correlations in 220 classrooms in the Midwestern United States. *Building and Environment*, *157*(February), 79–88. https://doi.org/10.1016/j.buildenv.2019.04.038

Desimone, L. (1999). Linking parent involvement with student achievement: Do race and income matter? *Journal of Educational Research*, *93*(1), 11–30. https://doi.org/10.1080/00220679909597625

Dorizas, P. V., Assimakopoulos, M. N., Helmis, C., & Santamouris, M. (2015). An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring. *Science of the Total Environment*, *502*, 557–570. https://doi.org/10.1016/j.scitotenv.2014.09.060

Ebrahimifakhar, A., Kabirikopaei, A., & Yuill, D. (2020). Data-driven fault detection and diagnosis for packaged rooftop units using statistical machine learning classification methods. *Energy and Buildings*, *225*, 110318. https://doi.org/10.1016/j.enbuild.2020.110318

Eide, E., & Showalter, M. H. (1998). The effect of school quality on student performance: A quantile regression approach. *Economics Letters*, *58*(3), 345–350. https://doi.org/10.1016/s0165-1765(97)00286-3

EPA. (1987). *The total exposure assessment methodology (TEAM) study: Summary and analysis.*

EPA. (2015). *Healthy Schools: Environmental Factors, Children's Health and Performance, and Sustainable Building Practices*. https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/recipients.display/rfa_id/568/records_per_page/ALL

Everett Jones, S., Smith, A. M., Wheeler, L. S., & McManus, T. (2010). School Policies and Practices That Improve Indoor Air Quality. *Journal of School Health*, *80*(6), 280–286. https://doi.org/10.1111/j.1746-1561.2010.00502.x

Figliola, R. S., & Beasley, D. E. (2006). *Theory and design for mechanical measurements* (Fourth). John Wiley & Sons.

Finell, E., Tolvanen, A., Haverinen-shaughnessy, U., Laaksonen, S., Karvonen, S., Sund, R., Luopa, P., Pekkanen, J., & Ståhl, T. (2018). Science of the Total Environment Indoor air problems and the perceived social climate in schools : A multilevel structural equation analysis. *Science of the Total Environment*, *624*, 1504–1512. https://doi.org/10.1016/j.scitotenv.2017.12.126

Fischer, A., Ljungström, E., Hägerhed Engman, L., & Langer, S. (2015). Ventilation strategies and indoor particulate matter in a classroom. *Indoor Air*, *25*(2), 168–175. https://doi.org/10.1111/ina.12133

Fischer, Andreas, Ljungström, E., & Langer, S. (2013). Ozone removal by occupants in a classroom. *Atmospheric Environment*, *81*, 11–17. https://doi.org/10.1016/j.atmosenv.2013.08.054

Fisk, W. J. (2017). The ventilation problem in schools: literature review. *Indoor Air*, *27*(6), 1039–1051. https://doi.org/10.1111/ina.12403

Gao, J., Wargocki, P., & Wang, Y. (2014). Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms. *Building and Environment*, *75*, 46–57. https://doi.org/10.1016/j.buildenv.2014.01.015

Godwin, C., & Batterman, S. (2007). Indoor air quality in Michigan schools. *Indoor Air*, *17*(2), 109–121. https://doi.org/10.1111/j.1600-0668.2006.00459.x

Goodman, J., Hurwitz, M., Park, J., Smith, J., Katz, L., Aldy, J., Barreca, A., Deschenes, O., Reber, S., Yin, W., Shah, M., Boomhower, J., Garg, T., Jacobsen, M., & Behrer, P. (2018). NBER WORKING PAPER SERIES HEAT AND LEARNING Heat and Learning. *NATIONAL BUREAU OF ECONOMIC RESEARCH*. http://www.nber.org/papers/w24639

Guo, H., Morawska, L., He, C., & Gilbert, D. (2008). Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air-conditioned classroom. *Atmospheric Environment*, *42*(4), 757–768. https://doi.org/10.1016/j.atmosenv.2007.09.070

Ha, B. O. (2012). *Novel second-degree solution to single zone mass-balance equation improves the use of build-up data in estimating ventilation rates in classrooms*. 14–19. https://doi.org/10.1016/j.jchas.2012.12.001

Hakuta, K., Butler, Y. G., & Witt, D. (2000). *How Long Does It Take To Have English Proficiency*.

Harwell, M., & LeBeau, B. (2010). Student eligibility for a free lunch as an ses measure in education research. *Educational Researcher*, *39*(2), 120–131. https://doi.org/10.3102/0013189X10362578

Haverinen-Shaughnessy, U., Moschandreas, D. J., & Shaughnessy, R. J. (2011a). Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air*, *21*(2), 121–131. https://doi.org/10.1111/j.1600-0668.2010.00686.x

Haverinen-Shaughnessy, U., Moschandreas, D. J., & Shaughnessy, R. J. (2011b). *Association between substandard classroom ventilation rates and students Õ academic achievement*. 121–131. https://doi.org/10.1111/j.1600-0668.2010.00686.x

Haverinen-Shaughnessy, Ulla, & Shaughnessy, R. J. (2015). Effects of classroom ventilation rate and temperature on students' test scores. *PLoS ONE*, *10*(8), e0136165. https://doi.org/10.1371/journal.pone.0136165

Haverinen-Shaughnessy, Ulla, Shaughnessy, R. J., Cole, E. C., Toyinbo, O., & Moschandreas, D. J. (2015). An assessment of indoor environmental quality in schools and its association with health and performance. *Building and Environment*, *93*(P1), 35–40. https://doi.org/10.1016/j.buildenv.2015.03.006

Hodgson, A. T., Apte, M. G., & Shendell, D. G. (2002). *Implementation of VOC source reduction practices in a manufactured house and in school classrooms*.

Holmberg, I., & Wyon, D. P. (1969). The dependence of performance in school on classroom temperature. In: Educational and psychological interactions. *Educational and Psychological Interactions*, *31*, 20.

Hyde, J. S., Lindberg, S. M., Linn, M. C., Ellis, A. B., & Williams, C. C. (2008). Math Performance. *Science*, *321*(July), 494–495.

ISO. (2010). *ISO GUIDE 98-1:2009(E) Uncertainty of measurement — Part 1 : Introduction to the expression of uncertainty in measurement*.

Istrate, M. A., Catalina, T., Cucos, A., & Dicu, T. (2016). Experimental Measurements of VOC and Radon in Two Romanian Classrooms. *Energy Procedia*, *85*(November 2015), 288–294. https://doi.org/10.1016/j.egypro.2015.12.254

Jacqueline S. Zweig, John C. Ham, & Edward L. Avol. (2009). *Air Pollution and Academic Performance: Evidence from California Schools*.

Jamaludin, N. M., Mahyuddin, N., & Akashah, F. W. (2016). Assessment of Indoor Environmental Quality (IEQ): Students Well-Being in University Classroom with the Application of Landscaping. *MATEC Web of Conferences*, *66*. https://doi.org/10.1051/matecconf/20166600061

Johnson, D. L., Lynch, R. A., Floyd, E. L., Wang, J., & Bartels, J. N. (2018). Indoor air quality in classrooms : Environmental measures and e ff ective ventilation rate modeling in urban elementary schools. *Building and Environment*, *136*(March), 185–197. https://doi.org/10.1016/j.buildenv.2018.03.040

Kabirikopaei, A., Kuhlenengel, M., Arthur, A., Bovaird, J., Lau, J., Waters, C., & Wang, L. M. (2019). The Effects of Indoor Environmental Factors on Students' Academic Achievement. *AEI 2019*, *1*, 257–264. https://doi.org/10.1061/9780784482261.030

Kabirikopaei, A., & Lau, J. (2020). Uncertainty analysis of various CO2-Based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems. *Building and Environment*, *179*(December 2019), 107003. https://doi.org/10.1016/j.buildenv.2020.107003

Kielb, C., Lin, S., Muscatiello, N., Hord, W., Rogers-Harrington, J., & Healy, J. (2015). Building-related health symptoms and classroom indoor air quality: A survey of school teachers in New York State. *Indoor Air*, *25*(4), 371–380. https://doi.org/10.1111/ina.12154

Kim, J., & de Dear, R. (2018). Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students. *Building and Environment*, *127*(October 2017), 13–22. https://doi.org/10.1016/j.buildenv.2017.10.031

L, S., & Shaffran, J. (1973). A combined evaluation of three separate research projects on the effects of thermal environment on learning and performance. *ASHRAE Trans*, *79*, 97–108.

Labat, M., Woloszyn, M., Garnier, G., & Roux, J. J. (2013). Assessment of the air change rate of airtight buildings under natural conditions using the tracer gas technique. Comparison with numerical modelling. *Building and Environment*, *60*, 37–44. https://doi.org/10.1016/j.buildenv.2012.10.010

Lan, L., Xia, L., Hejjo, R., Wyon, D. P., & Wargocki, P. (2020). Perceived air quality and cognitive performance decrease at moderately raised indoor temperatures even when clothed for comfort. *Indoor Air*, *30*(5), 841–859. https://doi.org/10.1111/ina.12685

Lau, J., Liu, Y., & Johnson, K. (2020). Associating different indoor air contaminant levels with various ventilation systems in K-12 classrooms. *The 16th Conference of the International Society of Indoor Air Quality & Climate (Indoor Air 2020)*.

Leclerc, N., Wyart, G., Ramalho, O., Mullot, J.-U., Redaelli, M., Cabanes, P.-A., Blondeau, P., Boulanger, G., & Mandin, C. (2015). Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values. *Building and Environment*, *93*, 115–124. https://doi.org/10.1016/j.buildenv.2015.03.018

Madureira, J., Paciência, I., Pereira, C., Teixeira, J. P., & Fernandes, E. de O. (2016). Indoor air quality in Portuguese schools: levels and sources of pollutants. *Indoor Air*, *26*(4), 526–537. https://doi.org/10.1111/ina.12237

Madureira, Joana, Inês, P., João, R., & Elisabete, R. (2015). Indoor air quality in schools and its relationship with children ' s respiratory symptoms ^ s Paci e. *Atmospheric Environment*, *118*. https://doi.org/10.1016/j.atmosenv.2015.07.028

Majd, E., McCormack, M., Davis, M., Curriero, F., Berman, J., Connolly, F., Leaf, P., Rule, A., Green, T., Clemons-Erby, D., Gummerson, C., & Koehler, K. (2019). Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors. *Environmental Research*, *170*(December 2018), 83–91. https://doi.org/10.1016/j.envres.2018.12.012

Marks, G. N. (2016). The relative effects of socio-economic, demographic, non-cognitive and cognitive influences on student achievement in Australia. *Learning and Individual Differences*, *49*, 1–10. https://doi.org/10.1016/j.lindif.2016.05.012

Maxwell, L. E. (2016). School building condition, social climate, student attendance and academic achievement: A mediation model. *Journal of Environmental Psychology*, *46*, 206–216. https://doi.org/10.1016/j.jenvp.2016.04.009

Mendell, M. J., Eliseeva, E. A., Davies, M. M., & Lobscheid, A. (2016). Do classroom ventilation rates in California elementary schools influence standardized test scores ? Results from a prospective study. *Indoor Air*, *26*, 546–557. https://doi.org/10.1111/ina.12241

Mendell, M. J., Eliseeva, E. A., Davies, M. M., Spears, M., Lobscheid, A., Fisk, W. J., & Apte, M. G. (2013). Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. *Indoor Air*, *23*(6), 515–528. https://doi.org/10.1111/ina.12042

Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air*, *15*(1), 27–52. https://doi.org/10.1111/j.1600-0668.2004.00320.x

Mi, Y. H., Norbäck, D., Tao, J., Mi, Y. L., & Ferm, M. (2006). Current asthma and respiratory symptoms among pupils in Shanghai, China: Influence of building ventilation, nitrogen dioxide, ozone, and formaldehyde in classrooms. *Indoor Air*, *16*(6), 454–464. https://doi.org/10.1111/j.1600-0668.2006.00439.x

Moglia, D., Smith, A., MacIntosh, D. L., & Somers, J. L. (2006). Prevalence and implementation of IAQ programs in U.S. schools. *Environmental Health Perspectives*, *114*(1), 141–146. https://doi.org/10.1289/ehp.7881

Mohai, B. P., Kweon, B., Lee, S., & Ard, K. (2011). *Air Pollution Around Schools Is Linked To Poorer Student Health And Academic Performance*. *5*(5), 852–862.

Noda, L., Lima, A. V. P., Souza, J. F., Leder, S., & Quirino, L. M. (2020). Thermal and visual comfort of schoolchildren in air-conditioned classrooms in hot and humid climates. *Building and Environment*, *182*(May), 107156. https://doi.org/10.1016/j.buildenv.2020.107156

Norbäck, D., Hashim, J. H., Hashim, Z., & Ali, F. (2017). Volatile organic compounds (VOC), formaldehyde and nitrogen dioxide (NO2) in schools in Johor Bahru, Malaysia: Associations with rhinitis, ocular, throat and dermal symptoms, headache and fatigue. *Science of the Total Environment*, *592*, 153–160. https://doi.org/10.1016/j.scitotenv.2017.02.215

Oeder, S., Jörres, R. A., Weichenmeier, I., Pusch, G., Schober, W., Pfab, F., Behrendt, H., Schierl, R., Kronseder, A., Nowak, D., Dietrich, S., Fernández-Caldas, E., Lintelmann, J., Zimmermann, R., Lang, R., Mages, J., Fromme, H., & Buters, J. T. M. (2012). Airborne Indoor Particles from Schools Are More Toxic than Outdoor Particles. *American Journal of Respiratory Cell and Molecular Biology*, *47*(5), 575–582. https://doi.org/10.1165/rcmb.2012-0139OC

Othman, M., Latif, M. T., Yee, C. Z., Norshariffudin, L. K., Azhari, A., Halim, N. D. A., Alias, A., Sofwan, N. M., Hamid, H. H. A., & Matsumi, Y. (2020). PM2.5 and ozone in office environments and their potential impact on human health. *Ecotoxicology and Environmental Safety*, *194*(February), 110432. https://doi.org/10.1016/j.ecoenv.2020.110432

Park, J. (2016). *Temperature, Test Scores, and Educational Attainment*.

Park, J. H., Lee, T. J., Park, M. J., Oh, H. N., & Jo, Y. M. (2020). Effects of air cleaners and school characteristics on classroom concentrations of particulate matter in 34 elementary schools in Korea. *Building and Environment*, *167*(September 2019), 106437. https://doi.org/10.1016/j.buildenv.2019.106437

Pegas, P. N., Alves, C. A., Evtyugina, M. G., Nunes, T., Cerqueira, M., Franchi, M., Pio, C. A., Almeida, S. M., & Freitas, M. C. (2011). Indoor air quality in elementary schools of Lisbon in spring. *Environmental Geochemistry and Health*, *33*(5), 455–468. https://doi.org/10.1007/s10653-010-9345-3

Peng, S. S., & Hall, S. T. (1995). *Understanding racial-ethnic differences in secondary school science and mathematics achievement (NCES No. 95- 710)*. Department of Education.

Pepler, R. D., & Warner, R. E. (1968). Temperature and learning: an experimental study. *ASHRAE Transactions*, *74*(2), 211–219.

Persily, A. K. (1997). Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. *ASHRAE Transactions*, *103*, 193–204.

Persily, A. K. (2016). Field measurement of ventilation rates. *Indoor Air*, *26*(1), 97–111. https://doi.org/10.1111/ina.12193

Petty, T., Wang, C., & Harbaugh, A. P. (2013). Relationships Between Student, Teacher, and School Characteristics and Mathematics Achievement. *School Science and Mathematics*, *113*(7), 333–344. https://doi.org/10.1111/ssm.12034

Polednik, B. (2013). Particulate matter and student exposure in school classrooms in Lublin, Poland. *Environmental Research*, *120*, 134–139. https://doi.org/10.1016/j.envres.2012.09.006

Porras-Salazar, J. A., Wyon, D. P., Piderit-Moreno, B., Contreras-Espinoza, S., & Wargocki, P. (2018). Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils. *Indoor Air*, *28*(6), 892–904. https://doi.org/10.1111/ina.12501

Poulhet, G., Dusanter, S., Crunaire, S., Locoge, N., Gaudion, V., Merlen, C., Kaluzny, P., & Coddeville, P. (2014). Investigation of formaldehyde sources in French schools using a passive flux sampler. *Building and Environment*, *71*, 111–120. https://doi.org/10.1016/j.buildenv.2013.10.002

Quinn, D. M., & Cooc, N. (2015). Science Achievement Gaps by Gender and Race/Ethnicity in Elementary and Middle School: Trends and Predictors. *Educational Researcher*, *44*(6), 336–346. https://doi.org/10.3102/0013189X15598539

Rijnders, E., Janssen, N. A. H., van Vliet, P. H. N., & Brunekreef, B. (2001). Personal and outdoor nitrogen dioxide concentrations in relation to degree of urbanization and traffic density. *Environmental Health Perspectives*, *109*(SUPPL. 3), 411–417. https://doi.org/10.1289/ehp.01109s3411

Ronsse, L. M., & Wang, L. M. (2013). Relationships between unoccupied classroom acoustical conditions and elementary student achievement measured in eastern Nebraska. *The Journal of the Acoustical Society of America*, *133*(3), 1480–1495. https://doi.org/10.1121/1.4789356

Rosbach, J., Krop, E., Vonk, M., van Ginkel, J., Meliefste, C., de Wind, S., Gehring, U., & Brunekreef, B. (2016a). Classroom ventilation and indoor air quality—results from the FRESH intervention study. *Indoor Air*, *26*(4), 538–545. https://doi.org/10.1111/ina.12231

Rosbach, J., Krop, E., Vonk, M., van Ginkel, J., Meliefste, C., de Wind, S., Gehring, U., & Brunekreef, B. (2016b). Classroom ventilation and indoor air quality—results from the FRESH intervention study. *Indoor Air*, *26*(4), 538–545. https://doi.org/10.1111/ina.12231

Sadick, A. M., & Issa, M. H. (2017). Occupants' indoor environmental quality satisfaction factors as measures of school teachers' well-being. *Building and Environment*, *119*, 99–109. https://doi.org/10.1016/j.buildenv.2017.03.045

Salonen, H., Salthammer, T., & Morawska, L. (2018). Human exposure to ozone in school and office indoor environments. *Environment International*, *119*(July), 503–514. https://doi.org/10.1016/j.envint.2018.07.012

Salonen, H., Salthammer, T., & Morawska, L. (2019). Human exposure to NO2 in school and office indoor environments. *Environment International*, *130*(June), 104887. https://doi.org/10.1016/j.envint.2019.05.081

Salthammer, T. (2019). Formaldehyde sources, formaldehyde concentrations and air exchange rates in European housings. *Building and Environment*, *150*(October 2018), 219–232. https://doi.org/10.1016/j.buildenv.2018.12.042

Scheff, P. A., Paulius, V. K., Huang, S. W., & Conroy, L. M. (2000). Indoor air quality in a middle school, part i: Use of co2 as a tracer for effective ventilation. *Applied Occupational and Environmental Hygiene*, *15*(11), 824–834. https://doi.org/10.1080/10473220050175706

Shaftel, J., Belton-Kocher, E., Glasnapp, D., & Poggio, J. (2006). The impact of language characteristics in mathematics test items on the performance of English language learners and students with disabilities. *Educational Assessment*, *11*(2), 105–126. https://doi.org/10.1207/s15326977ea1102_2

Shaughnessy, R. J., Haverinen-Shaughnessy, U., Nevalainen, A., & Moschandreas, D. (2006). A preliminary study on the association between ventilation rates in classrooms and student performance. *Indoor Air*, *16*(6), 465–468. https://doi.org/10.1111/j.1600-0668.2006.00440.x

Shaughnessy, R., & Vu, H. (2012). Particle loadings and resuspension related to floor coverings in chamber and in occupied school environments. *Atmospheric Environment*, *55*, 515–524. https://doi.org/10.1016/j.atmosenv.2012.04.008

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004a). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air*, *14*(5), 333–341. https://doi.org/10.1111/j.1600-0668.2004.00251.x

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004b). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air*, *14*(5), 333–341. https://doi.org/10.1111/j.1600-0668.2004.00251.x

Sherman, M. H. (1989). Analysis of errors associated with passive ventilation measurement techniques. *Building and Environment*. https://doi.org/10.1016/0360-1323(89)90002-4

Smedje, G., & Norbäck, D. (2001). Incidence of asthma diagnosis and self-reported allergy in relation to the school environment - A four-year follow-up study in schoolchildren. *International Journal of Tuberculosis and Lung Disease*, *5*(11), 1059–1066.

Stafford, T. M. (2015). Indoor air quality and academic performance. *Journal of Environmental Economics and Management*, *70*, 34–50. https://doi.org/10.1016/j.jeem.2014.11.002

Tang, X., Misztal, P. K., Nazaroff, W. W., & Goldstein, A. H. (2016). Volatile organic compound emissions from humans indoors. *Environmental Science and Technology*, *50*(23), 12686–12694. https://doi.org/10.1021/acs.est.6b04415

Thiele, T., Singleton, A., Pope, D., & Stanistreet, D. (2016). Predicting students' academic performance based on school and socio-demographic characteristics. *Studies in Higher Education*, *41*(8), 1424–1446. https://doi.org/10.1080/03075079.2014.974528

Thomas, J., & Stockton, C. (2003). Socioeconomic status, race, gender, & retention: Impact on student achievement. *Essays in Education*, *7*.

Toftum, J., Kjeldsen, B. U., Wargocki, P., Menå, H. R., Hansen, E. M. N., & Clausen, G. (2015). Association between classroom ventilation mode and learning outcome in Danish schools. *Building and Environment*, *92*, 494–503. https://doi.org/10.1016/j.buildenv.2015.05.017

Toyinbo, O., Shaughnessy, R., Turunen, M., & Putus, T. (2016). *Building characteristics , indoor environmental quality , and mathematics achievement in Finnish elementary schools*. *104*, 114–121. https://doi.org/10.1016/j.buildenv.2016.04.030

Turanjanin, V., Vučićević, B., Jovanović, M., Mirkov, N., & Lazović, I. (2014). Indoor

CO2 measurements in Serbian schools and ventilation rate calculation. *Energy*, *77*, 290–296. https://doi.org/10.1016/j.energy.2014.10.028

U.S. EPA. (2020a). *Formaldehyde*. https://www.epa.gov/formaldehyde

U.S. EPA. (2020b). *Indoor Air Pollution and Health*. https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality

U.S. EPA. (2020c). *Indoor Particulate Matter*. https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter

U.S. EPA. (2020d). *Nitrogen Dioxide (NO2) Pollution*. https://www.epa.gov/no2-pollution/basic-information-about-no2

U.S. EPA. (2020e). *Ozone (O3) Air Quality Standards*. https://www.epa.gov/naaqs/ozone-o3-air-quality-standards

U.S. EPA. (2020f). *Volatile Organic Compounds' Impact on Indoor Air Quality*. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality

van der Zee, S. C., Strak, M., Dijkema, M. B. A., Brunekreef, B., & Janssen, N. A. H. (2017). The impact of particle filtration on indoor air quality in a classroom near a highway. *Indoor Air*, *27*(2), 291–302. https://doi.org/10.1111/ina.12308

Wade, M. O. (2017). *Formaldehyde in High School Classrooms*.

Wang, L. M. (2015). *School Environmental Effects on Student Achievement (SEESA)*. https://engineering.unl.edu/healthy-schools/

Wargocki, P., Porras-Salazar, J. A., & Contreras-Espinoza, S. (2019). The relationship between classroom temperature and children's performance in school. *Building and Environment*, *157*(April), 197–204. https://doi.org/10.1016/j.buildenv.2019.04.046

Wargocki, P., Porras-Salazar, J. A., Contreras-Espinoza, S., & Bahnfleth, W. (2020). The relationships between classroom air quality and children's performance in school. *Building and Environment*, *173*(December 2019), 106749. https://doi.org/10.1016/j.buildenv.2020.106749

Wargocki, P., & Wyon, D. P. (2007). *The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257)*. *163*(2), 193–220. https://doi.org/https://doi.org/10.1080/10789669.2007.10390951

Wargocki, P., & Wyon, D. P. (2013). Providing better thermal and air quality conditions in school classrooms would be. *Building and Environment*, *59*, 581–589. https://doi.org/10.1016/j.buildenv.2012.10.007

Wargocki, P., Wyon, D. P., Lynge-Jensen, K., & Bornehag, C. G. (2008). The effects of electrostatic particle filtration and supply-air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *HVAC and R Research*, *14*(3), 327–344. https://doi.org/10.1080/10789669.2008.10391012

Weschler, C. J., Shields, H. C., & Naik, D. V. (1989). Indoor Ozone Exposures. *Journal of the Air Pollution Control Association*, *39*(12), 1562–1568. https://doi.org/10.1080/08940630.1989.10466650

Woltman, H., Feldstain, A., MacKay, J. C., & Rocchi, M. (2012). An introduction to hierarchical linear modeling. *Quantitative Methods for Psychology*, *8*(1), 52–69. https://doi.org/10.20982/tqmp.08.1.p052

Wößmann, L. (2003). Schooling resources, educational institutions and student performance: The international evidence. *Oxford Bulletin of Economics and Statistics*, *65*(2), 117–170. https://doi.org/10.1111/1468-0084.00045

Wyon DP. (1970). Studies of children under imposed noise and heat stress. *ERGONOMICS*, *13*(5), 598–612.

Yu, C. K. H., Li, M., Chan, V., & Lai, A. C. K. (2014). Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration. *Building and Environment*, *76*, 73–80. https://doi.org/10.1016/j.buildenv.2014.03.004

Yuan, Y., Luo, Z., Liu, J., Wang, Y., & Lin, Y. (2018). Health and economic benefits of building ventilation interventions for reducing indoor PM2.5 exposure from both indoor and outdoor origins in urban Beijing, China. *Science of the Total Environment*, *626*, 546–554. https://doi.org/10.1016/j.scitotenv.2018.01.119

Zweig, J. S., Ham, J. C., & Avol, E. L. (2009). *Evidence from California Schools*.

APPENDIX A- Correlation study for seasonal IAQ and TC variables

In appendix A, the results of correlation study for the rest of IAQ and thermal variables (continue from section 4.5.1) are presented.

- **Coarse Particles**

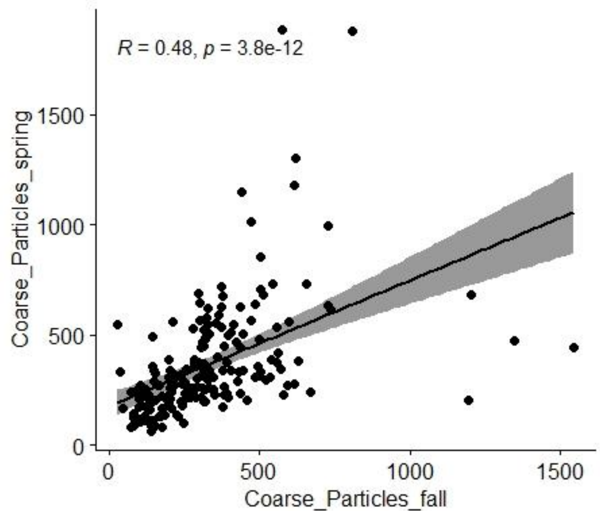


Figure A-1: coarse particels range and correlations in fall & spring

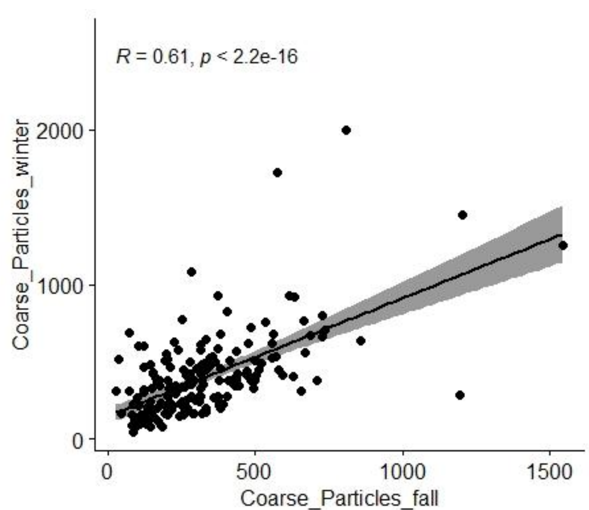


Figure A-2: coarse particels range and correlations in fall & winter

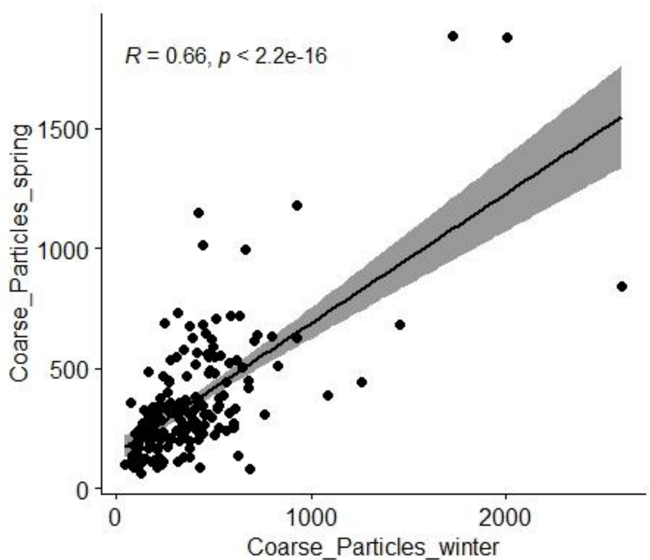


Figure A-3: coarse particels range and correlations in spring & winter

- **Ozone**

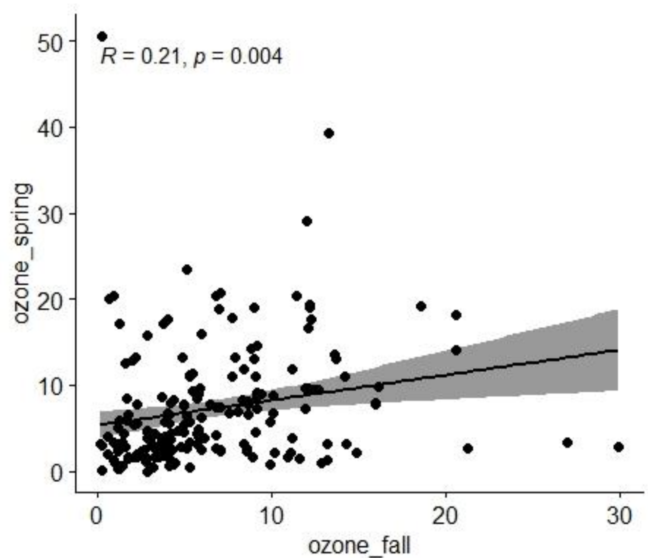


Figure A-4: ozone range and correlations in fall & spring

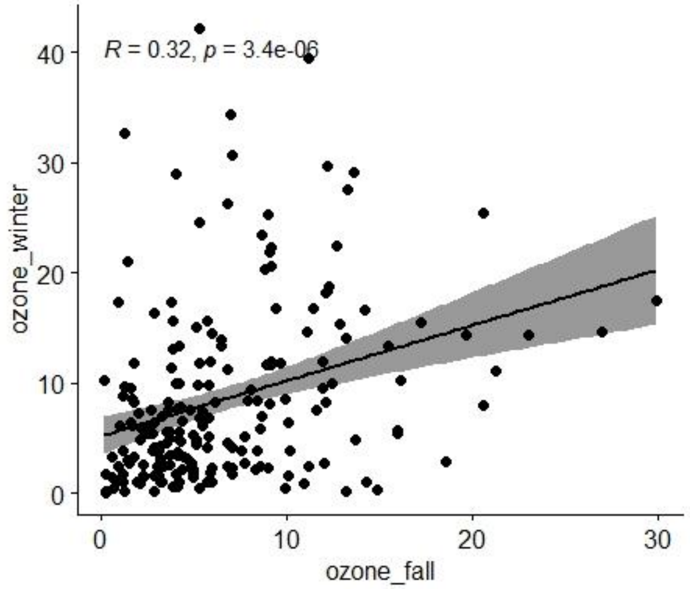


Figure A-5: ozone range and correlations in fall & winter

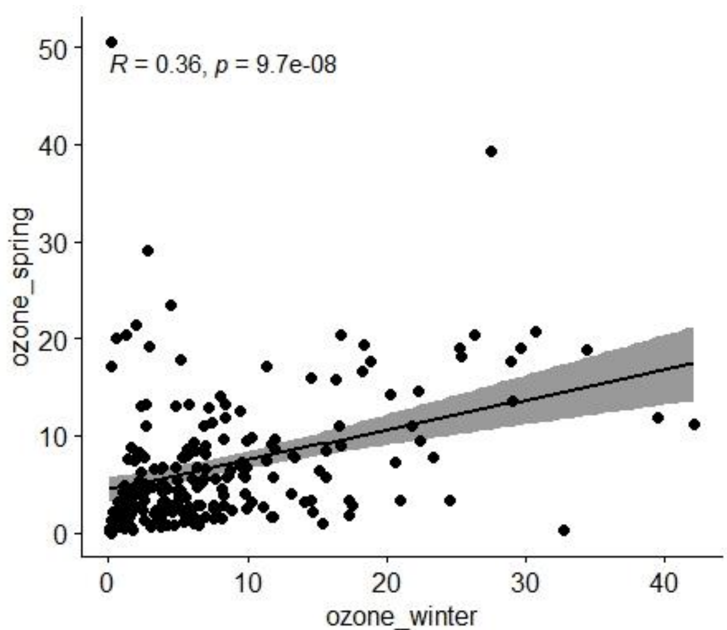


Figure A-6: ozone range and correlations in winter & spring

- **TVOC**

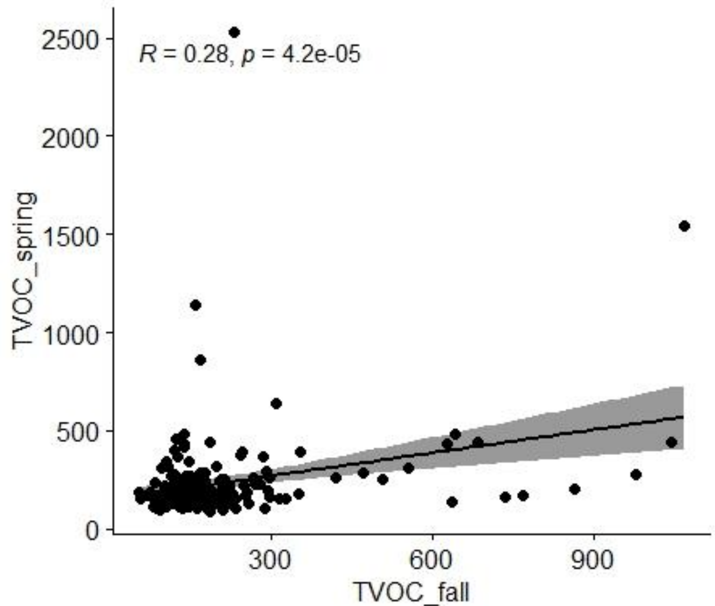


Figure A-7: TVOC range and correlations in fall & spring

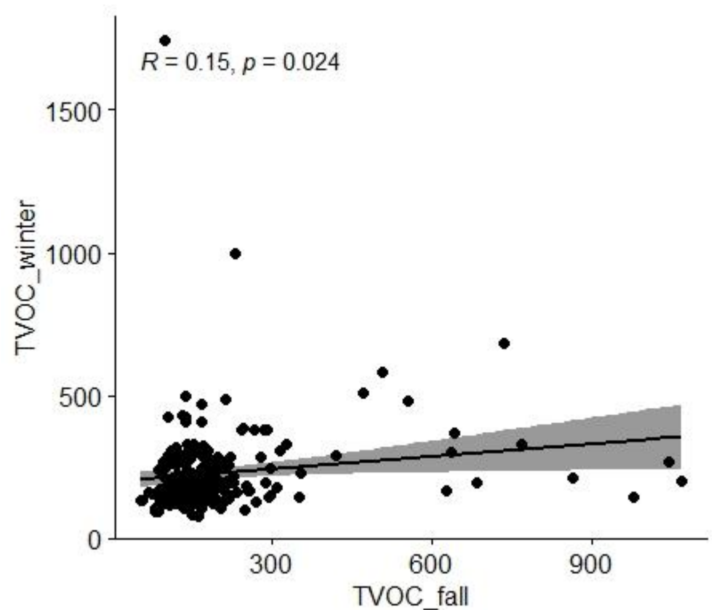


Figure A-8: TVOC range and correlations in fall & winter

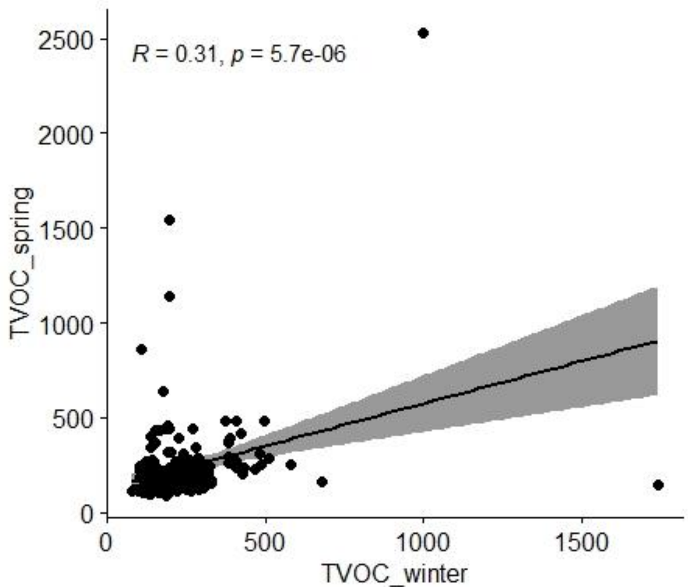


Figure A-9: TVOC range and correlations in spring & winter

- **NO_2**

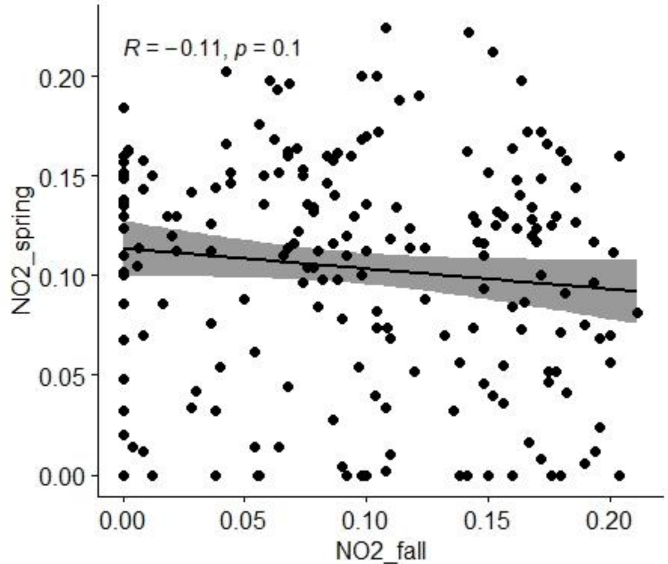


Figure A-10: TVOC range and correlations in fall & spring

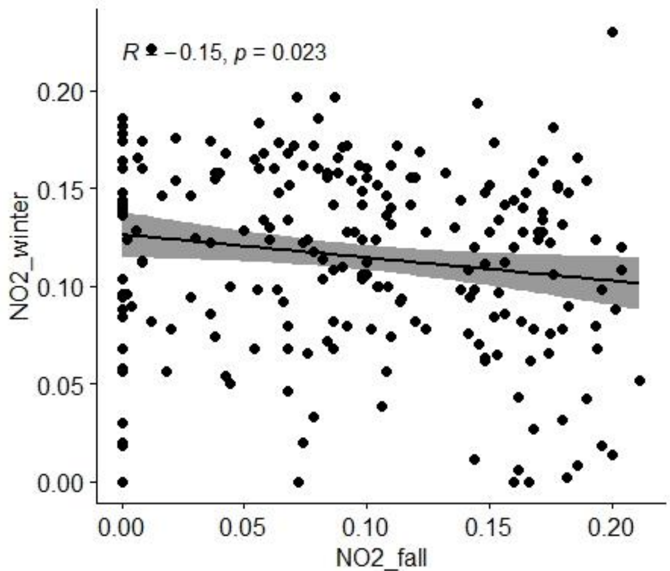


Figure A-11: NO_2 range and correlations in fall & winter

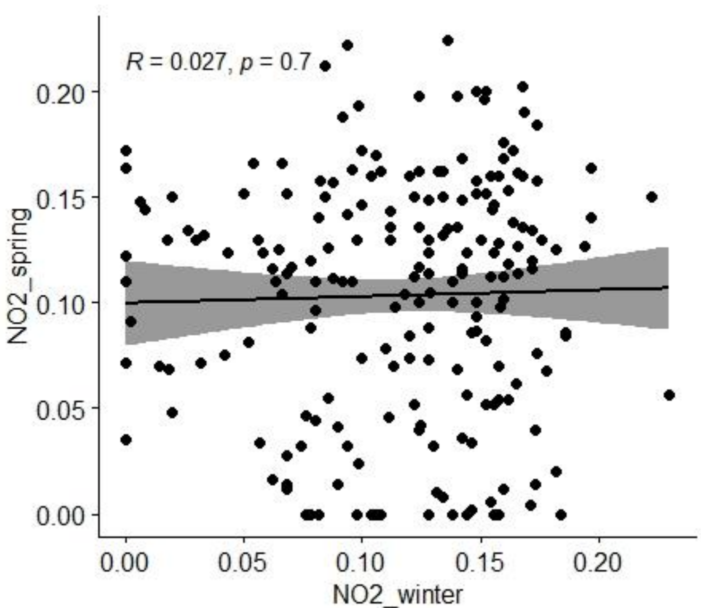


Figure A-12: NO_2 range and correlations in winter & spring

- **CO**

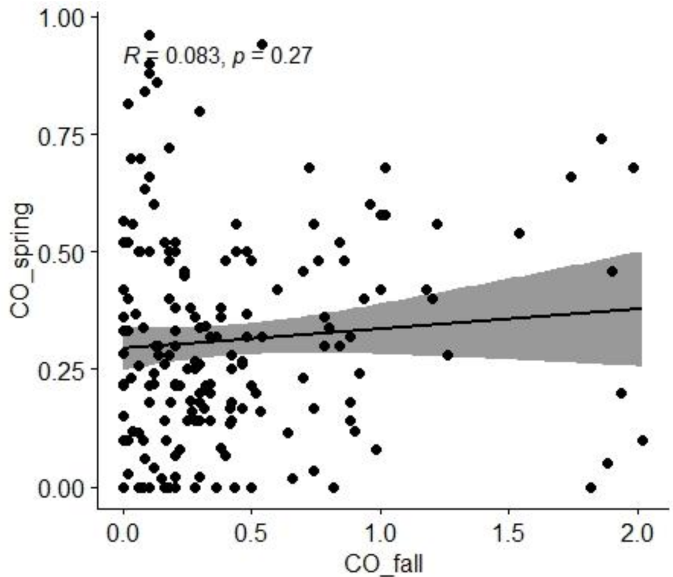


Figure A-13: CO range and correlations in fall & spring

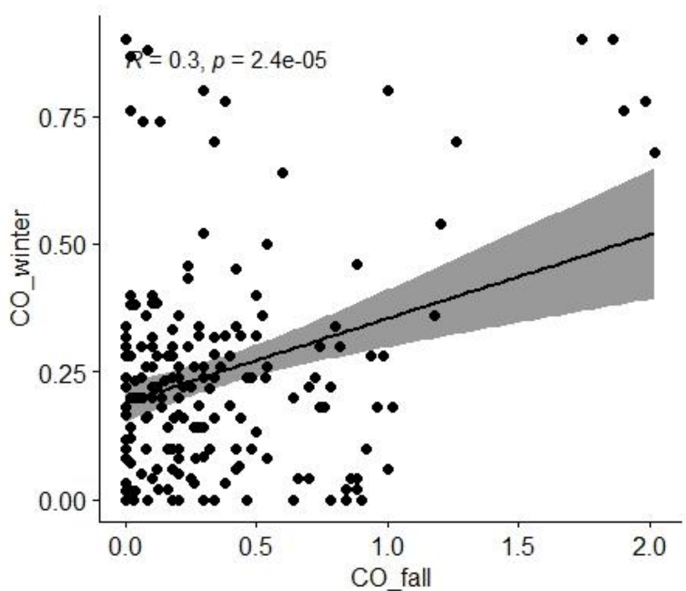


Figure A-14: CO range and correlations in fall & winter

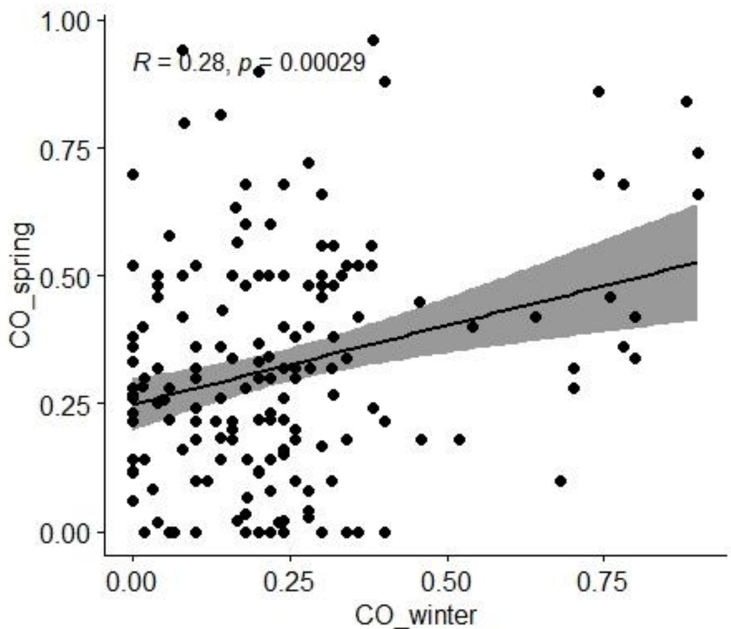


Figure A-15: CO range and correlations in winter & spring

APPENDIX B- Interaction plots for demographics and IAQ, TC variables

The interactions plots have been presented in this section. In these plots the slope of the variable in the model and the total slope (interaction's slope + main effect's slope) have been compared.

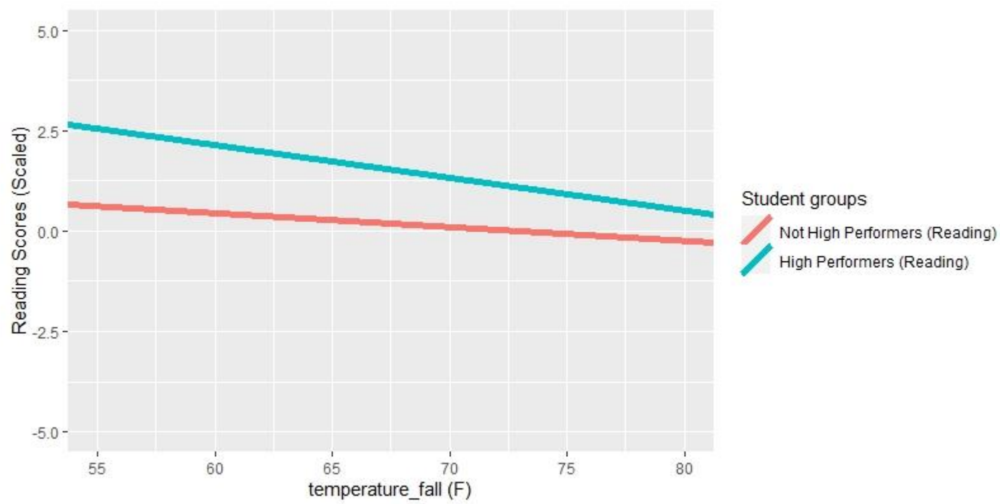


Figure B-1: Interaction plot for temperature (fall) and high performers

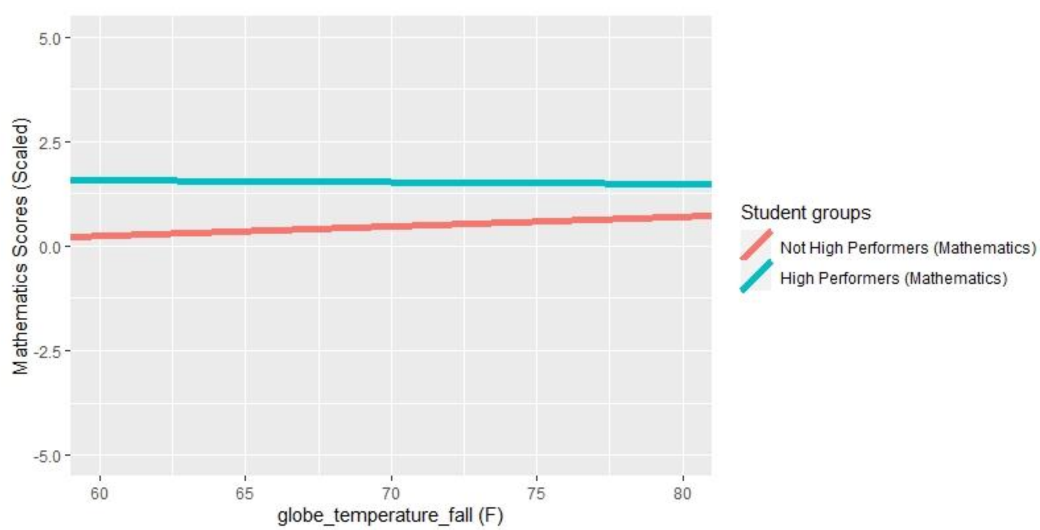


Figure B-2: Interaction plot for globe temperature (fall) and high performers

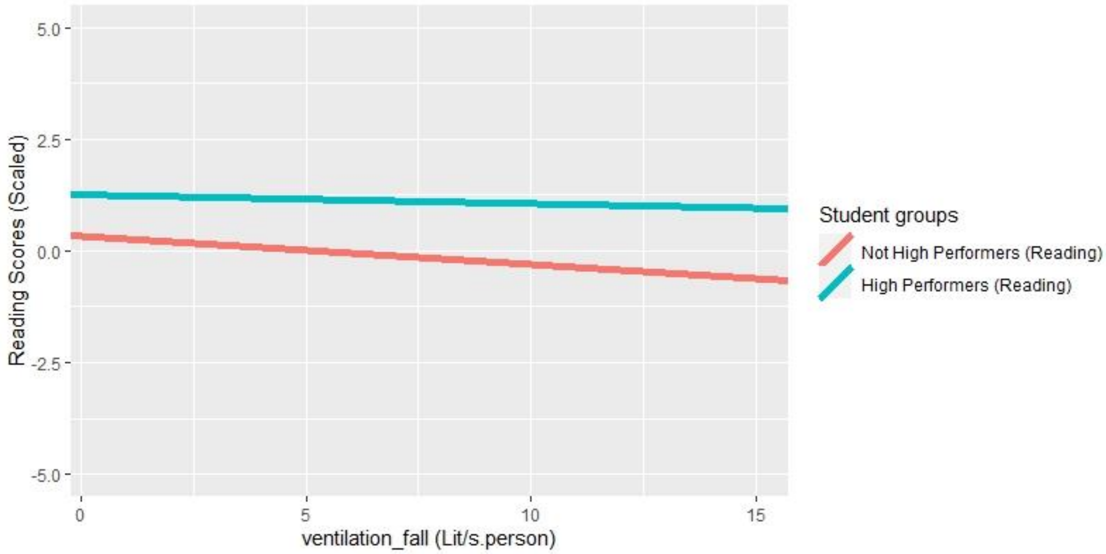


Figure B-3: Interaction plot for ventilation (fall) and high performers

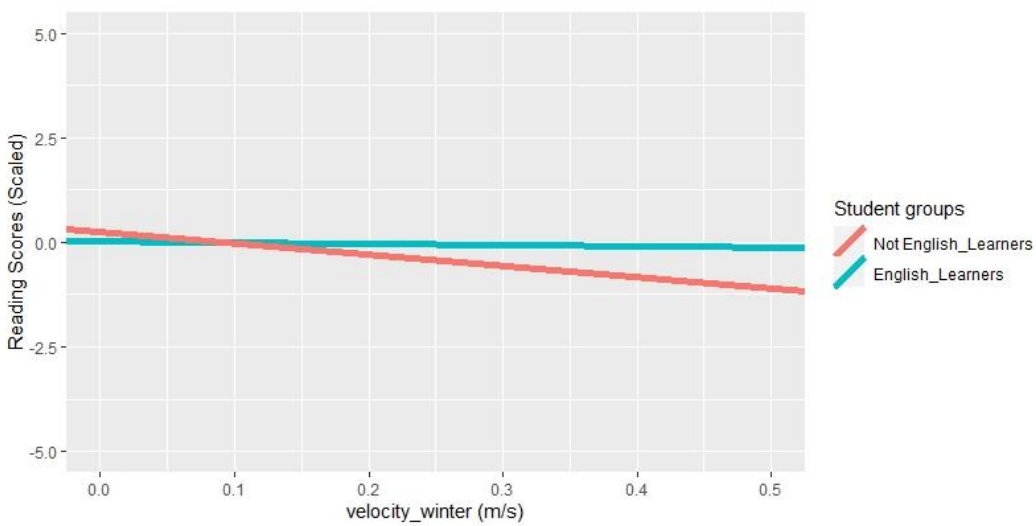


Figure B-4: Interaction plot for globe temperature (fall) and English learners

APPENDIX C- Statistical models without performance variables

Statistical models without the performance variable (as the input) were fit for each elementary and middle/ high school model. The results are presented in this section.

1. Elementary Schools (Response = Mathematics)

Table C-1: Elementary Schools (Mathematics Scores), AIC = 4018.2

Input Variables	**Estimate**	**Standard Error**	**p-value**	**Significance level**
(Intercept)	0.4042	0.1345	0.0031	**
system_typeSingle-Zone	-0.2213	0.1336	0.1016	
Gender1	-0.1324	0.0487	0.0066	**
Free_Reduced_lunch1	-0.5341	0.0634	< 2e-16	***
White_notWhite1	0.1116	0.0845	0.1868	
English_Learners1	-0.1066	0.1162	0.3591	
formaldehyde_fall	0.0217	0.0468	0.6442	
globe_temperature_fall	0.0516	0.0343	0.1375	
globe_temperature_spring	-0.0660	0.0376	0.0840	.
globe_temperature_winter	0.1115	0.0324	0.0010	***
pn_2.5_fall	0.0587	0.0823	0.4777	
pn_2.5_spring	-0.0036	0.0633	0.9550	
pn_2.5_winter	-0.0332	0.0675	0.6237	
pn_coarse_annual	0.0108	0.0411	0.7928	
relative_humidity_annual	0.0115	0.0584	0.8445	
temperature_fall	-0.0090	0.0337	0.7895	
temperature_spring	0.0692	0.0474	0.1496	
temperature_winter	-0.0120	0.0500	0.8103	
ventilation_fall	-0.0089	0.0643	0.8898	
ventilation_spring	0.0131	0.0433	0.7634	
ventilation_winter	-0.0154	0.0574	0.7889	
carbon_monoxide_annual	0.0350	0.0509	0.4941	
nitrogen_dioxide_annual	-0.0349	0.0375	0.3552	
Ozone_indoor_annual	-0.0347	0.0488	0.4806	
TVOC_annual	0.0079	0.0437	0.8572	
velocity_fall	-0.0294	0.0424	0.4893	
velocity_spring	0.1240	0.0445	0.0070	**
velocity_winter	0.0473	0.0630	0.4563	

2. Elementary Schools (Response = Reading)

Table C-2: Elementary Schools (Reading Scores), AIC = 4023.9

Input Variables	Estimate	Standard Error	p-value	Significance level
(Intercept)	-0.1044	0.1279	0.4152	
system_typeSingle-Zone	0.2516	0.1242	0.0457	*
Gender1	0.1657	0.0489	0.0007	***
Free_Reduced_lunch1	-0.5572	0.0632	< 2e-16	***
White_notWhite1	0.1097	0.0848	0.1959	
English_Learners1	-0.3129	0.1176	0.0079	**
formaldehyde_fall	-0.0923	0.0432	0.0359	*
globe_temperature_fall	0.0444	0.0316	0.1632	
globe_temperature_spring	-0.0548	0.0346	0.1170	
globe_temperature_winter	0.0599	0.0298	0.0478	*
pn_2.5_fall	-0.0328	0.0763	0.6682	
pn_2.5_spring	-0.0142	0.0585	0.8093	
pn_2.5_winter	0.1305	0.0626	0.0397	*
pn_coarse_annual	0.0176	0.0377	0.6417	
relative_humidity_annual	-0.0599	0.0541	0.2711	
temperature_fall	-0.0501	0.0310	0.1104	
temperature_spring	-0.0549	0.0435	0.2115	
temperature_winter	0.0336	0.0461	0.4680	
ventilation_fall	-0.0690	0.0593	0.2480	
ventilation_spring	0.0324	0.0401	0.4212	
ventilation_winter	0.1269	0.0529	0.0187	*
carbon_monoxide_annual	0.0375	0.0468	0.4249	
nitrogen_dioxide_annual	-0.0168	0.0345	0.6277	
Ozone_indoor_annual	0.0669	0.0447	0.1392	
TVOC_annual	-0.0830	0.0401	0.0419	*
velocity_fall	0.0463	0.0389	0.2374	
velocity_spring	0.0094	0.0408	0.8190	
velocity_winter	-0.1659	0.0591	0.0063	**
English_Learners1:velocity_winter	0.1817	0.0896	0.0427	*

Middle/ High schools (Response = Mathematics)

Table C-3: Middle/ High Schools (Mathematics Scores), AIC = 3877.6

Input Variables	Estimate	Standard Error	p-value	Significance level
(Intercept)	-5.0310	1.6477	0.0023	**
system_typeSingle-Zone	8.3214	2.6534	0.0018	**
Gender1	0.0085	0.0490	0.8618	
Free_Reduced_lunch1	-0.3605	0.0599	0.0000	***
White_notWhite1	0.0478	0.0793	0.5463	
English_Learners1	-0.0170	0.1138	0.8815	
formaldehyde_fall	1.5282	2.0663	0.4597	
globe_temperature_fall	-0.2483	0.1532	0.1052	
globe_temperature_spring	0.5184	1.0210	0.6117	
globe_temperature_winter	0.9282	1.9422	0.6328	
pn_2.5_fall	-2.0539	0.4399	0.0000	***
pn_2.5_spring	1.0794	1.3202	0.4138	
pn_2.5_winter	-2.2863	2.8207	0.4178	
pn_coarse_annual	1.8258	2.0819	0.3806	
relative_humidity_annual	-1.7541	3.2758	0.5924	
temperature_fall	0.3844	0.4230	0.3637	
temperature_spring	-1.2901	1.9588	0.5103	
temperature_winter	-0.1939	1.1391	0.8649	
ventilation_fall	-1.1571	2.6167	0.6584	
ventilation_spring	1.5890	0.9884	0.1081	
ventilation_winter	0.4429	1.3131	0.7359	
carbon_monoxide_annual	-0.0254	0.2027	0.9002	
nitrogen_dioxide_annual	0.9707	2.0278	0.6322	
Ozone_indoor_annual	0.5230	0.4535	0.2490	
TVOC_annual	2.1268	1.4815	0.1513	
velocity_fall	-0.6817	0.7521	0.3649	
velocity_spring	-0.8355	1.0377	0.4209	
velocity_winter	0.0276	1.3839	0.9841	
Free_Reduced_lunch1: ventilat ion_winter	0.11734	0.0538	0.0292	*

Middle/ High schools (Response = Reading)

Table C-4: Middle/ High Schools (Reading Scores), AIC = 4564.3

Input Variables	Estimate	Standard Error	p-value	**Significance level**
(Intercept)	-1.2290	0.7548	0.1038	
system_typeSingle-Zone	1.9130	1.0780	0.0761	.
Gender1	0.0949	0.0464	0.0411	*
Free_Reduced_lunch1	-0.3671	0.0585	0.0000	***
White_notWhite1	0.0600	0.0735	0.4144	
English_Learners1	-0.0939	0.1070	0.3806	
formaldehyde_fall	-0.5702	0.2462	0.0207	*
globe_temperature_fall	-0.2617	0.0986	0.0080	**
globe_temperature_spring	-0.3407	0.0907	0.0002	***
globe_temperature_winter	-0.3240	0.1018	0.0015	**
pn_2.5_fall	0.0057	0.1523	0.9701	
pn_2.5_spring	1.3570	0.3180	0.0000	***
pn_2.5_winter	-0.3708	0.1670	0.0265	*
pn_coarse_annual	-0.1263	0.0967	0.1919	
relative_humidity_annual	-0.6215	0.2837	0.0286	*
temperature_fall	-0.5241	0.2326	0.0244	*
temperature_spring	0.1399	0.1655	0.3979	
temperature_winter	0.0849	0.1044	0.4164	
ventilation_fall	-0.1153	0.0562	0.0406	*
ventilation_spring	0.3034	0.2170	0.1624	
ventilation_winter	-0.1903	0.1806	0.2922	
carbon_monoxide_annual	0.0631	0.1666	0.7050	
nitrogen_dioxide_annual	-0.8263	0.2036	0.0001	***
Ozone_indoor_annual	-0.1618	0.0937	0.0844	.
TVOC_annual	-0.2078	0.1868	0.2660	
velocity_fall	0.0639	0.1368	0.6404	
velocity_spring	-0.1308	0.1478	0.3762	
velocity_winter	-0.0406	0.1886	0.8297	
Free_Reduced_lunch1:pn_2.5_spring	-0.1244	0.0518	0.0164	*
Free_Reduced_lunch1:ventilation_winter	0.0480	0.0594	0.4195	

APPENDIX D- IAQ, TC data (the distribution of variables)

The correlations between annual IAQ, themal variables and the distributions of each varaiable are introduced in the below figure.

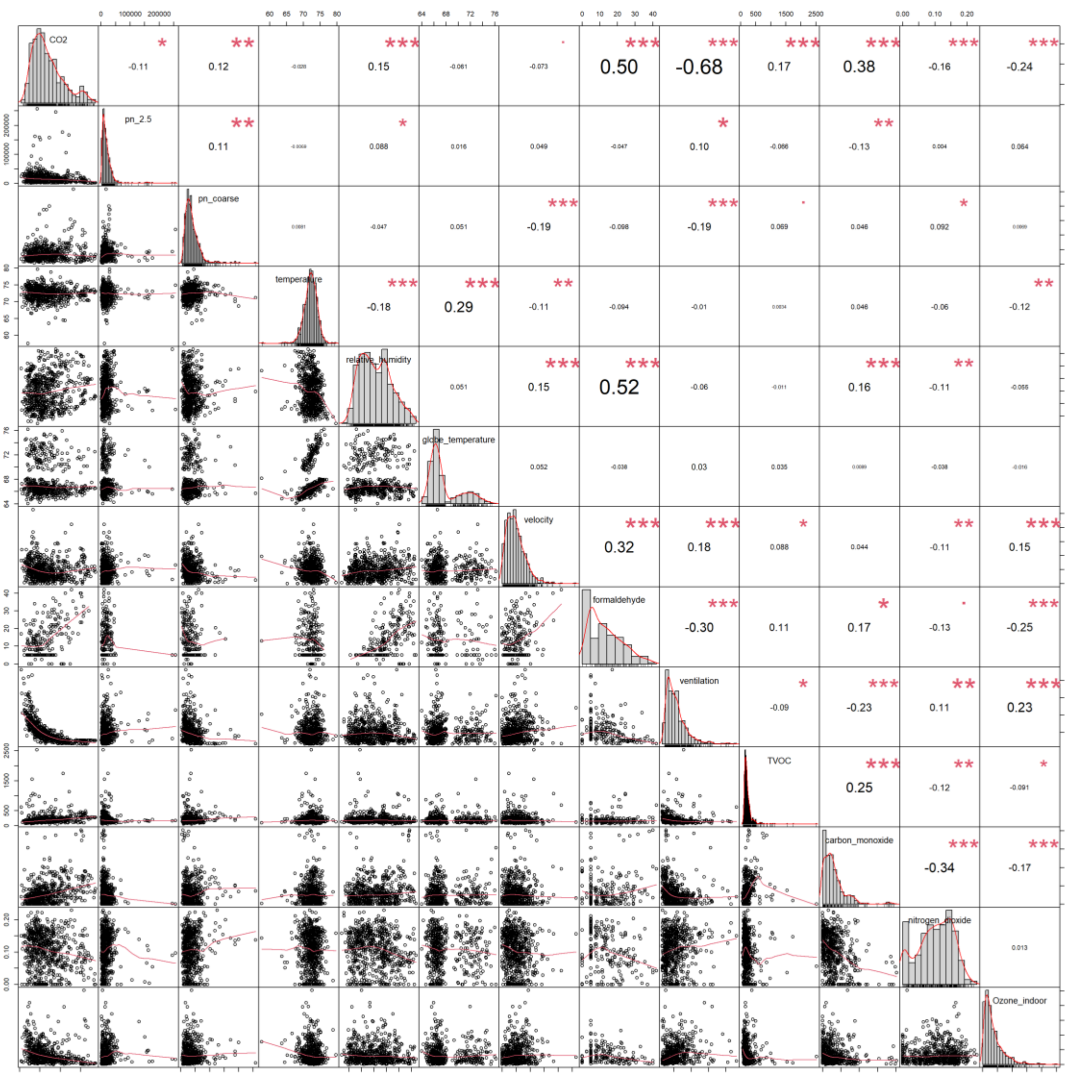


Figure D-1: Correlation between annual IAQ, themal variables and the distribution for each variable.