INDOOR ENVIRONMENTAL QUALITY IN CHILEAN CLASSROOM

by

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A DISSERTATION

Presented to the Department Architecture
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

September 2019

DISSERTATION APPROVAL PAGE

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Title: Indoor Environmental Quality in Chilean Classroom

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Degree awarded September 2019

DISSERTATION ABSTRACT

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Recently, there has been a growing concern about poor thermal comfort and air quality conditions that can have a negative effect on children's health and academic performance. Research in the U.S. and Europe has shown high classroom indoor temperatures and CO_2 concentrations, and low ventilation rates. Little is known about classroom conditions in developing countries like Chile, where there is no adherence to environmental standards. Additionally, there is limited knowledge about students' and teachers' perceptions of environmental conditions in primary schools. Furthermore, studies have shown that current thermal comfort standards criteria might not be applicable to children.

This thesis aims to advance our understanding of students' and teachers' perceptions of thermal comfort and indoor air quality in primary school settings. Moreover, this dissertation intends to identify other factors that may influence thermal and air quality comfort. The research questions are: 1) What are the physical conditions of classrooms in Chilean primary schools?; 2) What is the relationship between physical conditions of classrooms among the three types of schools (public, private–subsidized, and private non–subsidized) commonly found in Chile?; 3) Do expectations of thermal comfort and air quality differ between students and teachers?; and 4) Do subjective perceptions of classroom environmental qualities differ between the types of schools that represent different social/economic backgrounds?

Two field studies were conducted in nine free-running classrooms in the city of Concepción, Southern Chile. Various methods were implemented to collect data, based on previous studies on children: survey questionnaires, physical measurements, interviews, behavioral observations, and statistical analysis. Approximately 880 students, aged 10-14 years old, and 80 teachers were surveyed twice a day in the fall and winter season of 2018.

Overall, the results show that students and teachers were comfortable, despite low indoor temperatures and poor air quality conditions, outside the comfort zone limits of the ASHRAE–55 standard adaptive model. Analyses from subjective responses reveal 80% of comfort acceptability, thanks to personal adaptations. A statistically significant difference ($p<0.001$) in students' thermal perception was found between private-subsidized and public schools, and between private-subsidized and private-nonsubsidized schools.

This dissertation includes previously published and unpublished co-authored material.

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Rivera, M.I., and Kwok, A. (2019). *Thermal Comfort and Air Quality in Chilean Schools, Perceptions of Student and Teachers*. Proceedings from the ARCC Spring Research Conference, Toronto, Canada, May 29–June 1, 2019. Retrieved from https://www.arcc-repository.org/index.php/repository/article/view/632

Kwok, A., Tjahjana, N., & Rivera, M.I. (2017). *Campus Audit Squads for Energy (CASE): understanding behavioural patterns and energy use of plug loads*. Proceedings from PLEA Conference, Edinburgh, Scotland, July 2–5, Vol. I. Building Performance Evaluation (pp. 756–763) Retrieved from https://plea2017.net/

Delpino, M., and Rivera, M.I. (2017). *Architectural Design Studio as a tool to promote University Social Responsibility (USR) in the improvement of urban environments*. Proceedings from PLEA Conference, Edinburgh, Scotland, July 2–5. Vol. II. Education and Training (pp. 2259–2266). Retrieved from https://plea2017.net/

Elzeyadi, I., Abboushi, B., Hadipour, H., and Rivera, M.I. (2016). *High–Performance Facades: Measuring the Impacts of Dynamic Shading Prototypes on Indoor Environmental Quality Using Yearly Simulations and Field Test*. Proceedings *from* PLEA Conference, Los Angeles, California, United States, July 11–13. Vol. II. Strategies, tools, and simulation methods (pp. 1004–1013).

Agurto, L., Espinosa, P., Rivera, M.I., & Merino, L. (2015). *Develop of a set of criteria and sustainability indicators as a digital tool to assist the design at neighborhood scale on the Chilean context*. Proceedings from Organized by the Center and Faculty of Environmental Science, University of Concepción, Chile, March.

Delpino, M., Rivera, M.I. (2013). *Sustainable Construction: Recycle, reinterpret, rehabilitate as an exploration and experience in architectural and urban improvement. Proceedings from* 5th International Congress of Architecture and Environment, University of Concepción, Chile, November.

Rivera, M.I. (2010). *Chaitén Rebuilding from the Ashes: Sustainable Housing Prototype for an eco-village in southern Chile*. International Symposium: Sustainability and City Development, La Serena, Chile, October 2009. *Cuadernos de Investigación Urbanística, 0*(70). Retrieved from http://polired.upm.es/index.php/ciur/article/view/1180

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to my dissertation committee composed by Professors Alison Kwok, Alexandra Rempel, Kevin Van Den Wymelenberg, and Charles Martinez for the precious time, assistance, feedback, knowledge, and encouragement in the preparation of this manuscript. Additionally, I would like to thank Professor Lauren Lindstrom, for her guidance and feedback provided in the exam questions and early stages of my research. Professor Alison Kwok has been my trusted advisor and mentor throughout these four years. I have learned immensely from her, particularly how to spark in students their thirst for sustainable design, passive architecture, and building science. She has inspired and encouraged me to actively participate in promoting healthy sustainable design, getting to know great educators and experts in this field. I feel very fortunate that our paths did cross, and I would not be where I am today without her help, guidance, and support.

This research would have not been possible without the assistance of the Department of Education and Infrastructure of Municipalities of Concepción and San Pedro de la Paz, particularly architects and colleagues Javier Canales, Francisco Brito, Felipe Perez, and Angeline Arriata. Additionally, I thank all the students and teachers involved in this study for their patience, time, and generosity. I would also like to thank all the administration staff of the different schools who allowed me access to the different classrooms, provided feedback, and helped immensely in my fieldwork, in particular: Roberto Riquelme, Jose Vilche, Dory Zepeda , Leyla Acevedo, Flavia Molina, Gastón Torres, Maria Lourdes Alid, María Graciela Escárate, Gonzalo Sepúlveda, Susana Cabrera, Juan Pablo Duran, José Quezada, Gabriel Beguiristian, Domingo Seguel, and Víctor Viveros. My heartfelt appreciation to my students, Fresdly Lizama, Ignacio Galindo, and Sebastian Galindo, who assisted me during my fieldwork and gave me their commitment, patience and great learning moments. And also to my friend and teacher, Pamela Toledo, for her time, encouragement, and support-that was instrumental during surveys and follow-up interviews.

I am indebted to Universidad de Concepción for its financial support through the Universidad de Concepción scholarship, and to my current Dean, Leonel Perez, and former Dean Bernardo Suazo who encouraged me to pursue my Ph.D. My Ph.D. studies could have not been possible without the financial support from the Department of Architecture of the University of Oregon, during my first year, and from the National Commission for Scientific and Technological Research (CONICYT) through the Becas Chile–scholarship, during the next three consecutive years. Additionally, I very much appreciate the support from the Anthony Wong Scholarship for Research in Sustainable Design, the Ph.D. Architecture Fund, and the Society of Building Science Educators (SBSE) through their Student Retreat and Conference Scholarships, and the Jeffrey Cook Student Travel Scholarship.

I am very grateful to my great friend and colleague Lyndsey Deaton, for her constant support, advise, and therapeutic talks during the Ph.D. program. Thank you for making this process memorable!

Last but not least, my infinite gratitude to my extended family and friends, who have supported me from the beginning. To my family editors, Cathi, Paul, Doug, and Ricardo, for all those extra-long hours you help me "translate" and proofread my ideas. To my parents, for their prayers and encouragement that helped me to persevere. To Ricardo, for this crazy four-year journey we did together, your support, patience, knowledge, and generosity. This has been inspiring and kept me going throughout a successful achievement. I am forever grateful.
Gracias totales!

To all the childrens in Chile and in the rest of world, who deserve better learning environments.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

CHAPTER I:

INTRODUCTION

School learning environments are one of the most critical spaces where different aspects of sustainability research can be integrated, such as: indoor environmental quality, energy efficiency, performance, behavior, health, and well-being, and the effects it can have on occupants when these are poorly integrated or not considered at all in the design. Additionally, it is widely acknowledged that children spend a significant amount of time indoors, 80–90% between home and school (Klepeis et al., 2001), during their developmental years, from early childhood to adolescence. In virtually no other setting do people spend extended periods in such close quarters; the average school has an occupant density that can be somewhere between those of prisons and commercial planes (Frumkin, 2006).

Learning activities demand high levels of concentration, since students learn new topics and advance in their thinking skills; therefore, classroom design characteristics should provide a stimulating environment that promotes the learning process (De Giuli, Da Pos, & De Carli, 2012; Mishra & Ramgopal, 2013; Turunen et al., 2014). Studies have shown that high classroom indoor temperatures, (de Dear et al., 2013; Mendell & Heath, 2005; Wargocki & Wyon, 2007, 2013a) high CO_2 concentration levels, and low ventilation rates (Bakó-Biró, Clements-Croome, Kochhar, Awbi, Williams, 2012; Cui, Cao, Park, Ouyang, & Zhu, 2013a; Haverinen-Shaughnessy & Shaughnessy, 2015; Mendell et al., 2013) can have a negative impact on student performance and well-being. This is of particular concern in developing countries, such as Chile, where unfavorable environmental conditions (i.e., high CO_2 concentrations, high and low temperatures, and high RH) have been identified in schools (Soto, Trebilcock, & Pérez, 2015), and where there is no adherence to indoor environmental quality standards, or ordinances that can regulate minimum requirements. Closer attention to the indoor environmental quality (hereafter IEQ) conditions needs to be considered in order to promote health and performance enhancements.

As noted by Mendell & Heath (2005), young children are more susceptible to environmental pollutants than adults, because their developing lungs breathe more than twice the air compared to their bodies. Currently, many cities in the south of Chile, including Concepción city, have been declared saturated zones since 2015 for fine particles PM2.5 (Ministerio del Medio Ambiente de Chile (MMA), 2015), due to high air pollution from wood-burning heating systems typical of this region. These high concentrations are a concern because of the health impacts they can have on children in short- and long-term exposure. Additionally, looking at the building stock of current school design in Chile, the majority are free-running buildings (i.e., without heating or ventilation systems). Operable windows or doors are the only means of ventilation for providing fresh air in classrooms. Closer attention needs to be paid to the existing indoor climate of classrooms and its relationship to outdoor air pollutants, to promote comfort and well-being that support academic performance and user satisfaction.

Providing thermal comfort for occupants in a given environment not only depends on physical conditions but also on the interaction of physiological, psychological, emotional, cultural, and social factors of people (Fabbri, 2013, 2015). Current standards such as: ASHRAE–55 (2017); EN15251 (2007); ISO 10551 (1995); ISO 7726 (2001); and ISO 7730 (2005), define acceptable ranges of operative temperature based on heat balance and the adaptive thermal comfort models, from studies done in climate chambers simulating office environments with adult occupants only. Due to the absence of standards that deal specifically with indoor environmental quality in educational buildings and classroom spaces at different grade levels, architects and engineers must use current standards.

Recent studies have shown that children's perceptions and thermal preferences might differ from those of adults, because of physiological characteristics, and also because of the physical activities that children do in school buildings being different from sedentary ones in office settings (e.g., playground time, classroom presentations, and PE classes) (Mendell & Heath, 2005; Mors, Hensen, Loomans, & Boerstra, 2011; Zomorodian, Tahsildoost, & Hafezi, 2016b). Limited studies (Kwok, 1997) exist in which the perspectives of children and teachers regarding their perception of their indoor environment are combined in a single study. Understanding how their perceptions differ or compare can help our understanding of how to provide comfortable spaces for all of them. Additionally, some studies (Montazami, Gaterell, Nicol, Lumley, & Thoua, 2017b; Trebilcock, Soto-Muñoz, Yañez, & Figueroa-San Martin, 2017a) suggest that children's perceptions and preferences of thermal comfort might be influenced by other factors such as different social backgrounds.

In adaptive thermal comfort theory, Brager and de Dear (de Dear & Brager, 1998) argue that, "occupants are deemed as active agents in creating ideal indoor thermal conditions” (as cited in Kim and de Dear 2018) through adaptive strategies such as opening windows. In classrooms, however, school children have no control over windows, unless directed by a teacher. Studies have shown (De Giuli et al., 2012; Kim & de Dear, 2018b) that students in primary schools are less outspoken in expressing their desire to modify classroom environment to their teacher than older students in secondary schools. Additionally, school dress code policies, like the ones in Chilean schools, require students to wear school uniforms, limiting the opportunities to modify clothing during the day or to wear other clothing items that are not part of the uniform (Shamila Haddad, Osmond, & King, 2019). Therefore, more research is required in school buildings, particularly in the primary classroom level, to understand what adaptations are permissible between students and teachers in these settings.

1.1. Research Problem

The research gap this work address is understanding the degree to which school children and teachers can practice personal adaptive behaviors and how they interact with available opportunities to control their classroom environments is essential to understand the perceptions and expectations towards thermal comfort and indoor air quality acceptable to them. Additionally, we investigate how cultural and socio-economic background can play a role in a student's thermal comfort perceptions. Limited research has been conducted in this area (Montazami et al., 2017b; Trebilcock et al., 2017a), however both studies suggest that a strong relationship might exist between the socio-economic background of children and their thermal perceptions of classroom temperatures and home conditions. Children coming from more vulnerable backgrounds were more comfortable at lower temperatures than those considered less vulnerable (Trebilcock et al., 2017a). However, the study by Trebilcock et al. (2017a), only looks at public schools, and its scope is limited.

1.2. Research Objectives

Overall, this dissertation aims to advance our understanding of students' and teachers' perceptions of and sensations towards thermal comfort and indoor air quality in primary school settings. Moreover, this dissertation intends to identify other factors that may influence thermal and air quality comfort conditions in primary schools. Therefore, there are four objectives this study will address:

- To characterize the physical conditions of thermal and air quality (e.g. air temperature, relative humidity, air velocity, radiant temperature, CO_2 and particulate matter $PM_{2.5}$, PM_{10}) of school classrooms during different seasons, and compare them with thresholds from existing international standards and guidelines;

- To compare the thermal and air quality physical conditions between the three types of schools commonly found in Chile (public, private–subsidized, and private-nonsubsidized);

- To evaluate thermal comfort and indoor air quality perceptions and sensations of students and teachers in naturally ventilated classrooms;

- To evaluate whether perceptions of students of thermal and air quality comfort are related to their socio-economic background (the type of school, vulnerability index and home conditions).

1.3. Research Questions

To achieve these aims, this dissertation expands from the previous body of research by including comfort perceptions and sensations of both students and teachers in naturally–ventilated primary schools in Southern Chile. This study looks at contextual factors such as socio-economic background (the type of school, vulnerability index, and home conditions) that can influence the subject's perceptions of classroom environments.

The primary research questions this dissertation asks are:

1. What are the physical conditions of classrooms in Chilean primary schools?

2. How do physical conditions compare to international standards, such as ASHRAE-55?

3. What is the relationship between physical conditions of classrooms and the three types of schools (public, private–subsidized, and private non–subsidized) commonly found in Chile?

4. Do expectations of thermal comfort and air quality differ between students and teachers?

5. Do subjective perceptions of classroom environmental qualities differ between the types of schools that represent different social/economic backgrounds?

1.3.1. Hypothesis or Hypotheses

Three hypotheses inform this dissertation:

1. Primary school students perceive physical conditions of thermal comfort and air quality of their classrooms as unacceptable.

2. Classroom conditions would be unacceptable under international standards, such as ASHRAE-55 and EN15251.

3. There is a significant difference of students' thermal sensation perceptions between public and private schools. In public schools, TSVs fall on the colder side of the ASHRAE-55 7-point scale as compared to private schools.

1.4. Approach

This study focuses on a longitudinal survey approach consisting of real-time subjective responses with simultaneous physical measurements of thermal comfort and air quality in naturally–ventilated classrooms of nine primary school buildings, in the city of Concepcion, Chile.

Measurement protocols and data collection were based on ASHRAE-55-2017 Protocol I for thermal comfort and indoor air quality field studies which characterize the physical indoor environment while obtaining subjective responses. As it is evidenced in the literature review, field studies are more appropriate for observing and evaluating students' responses to naturally–ventilated environments.

Multiple approaches were implemented to collect and analyze data such as: physical measurements, survey questionnaires, interviews, observations, and statistical analysis commonly used in thermal comfort studies. However, this dissertation only reports on the results of quantitative data; (at this time, no qualitative analysis is presented from the results of teacher and student's interviews).

General approaches

- To characterize the physical conditions of thermal and air quality (e.g., air temperature, relative humidity, air velocity, radiant temperature, CO_2 and particulate matter $PM_{2.5}$, PM_{10}) of school classrooms during two seasonal regimes: fall and winter season.
- To compare measured physical conditions with comfort thresholds of the adaptive model of standard ASHRAE-55 (2017), WHO indoor air quality guidelines (WHO, 2010), and (ASHRAE-62.1, 2016) for classroom and school type.
- To evaluate and compare thermal comfort and indoor air quality perceptions and sensations responses of students and teachers to criteria specified in ASHRAE-55 (2017), using different comfort scales and environmental indices.
- To analyze whether students' perceptions of thermal and air quality comfort are related to their socio-economic background (the type of school, vulnerability index, and home conditions) through statistical analysis of variance and correlations.

- To compare the results with findings from other thermal comfort and air quality studies.

Preliminary approaches prior to the field study included: 1) assembly of participating schools and subject samples through a two-phase recruitment; 2) pilot studies with university students and teachers to test and check electronic survey questionnaires using tablets.

1.5. Significance

Classroom spaces are where children spend more time, other than home, during the developmental years of their life, up to one–third of the day (de Dear, Kim, Candido, & Deuble, 2015). It is known that environmental conditions that are not acceptable, due to poor ventilation, increased classroom temperatures, poor air quality, high levels of RH, can affect the comfort, health, and performance of children (de Dear et al., 2015; Kwok, 1997; Zeiler & Boxem, 2009). Thermal discomfort diverts attention; for example, cold conditions decrease finger temperatures, thus affecting manual dexterity (Chen, Shih, & Chi, 2010; Enander & Hygge, 1990; van Maanen et al., 2019; Willem, 2006). On the other hand, warm temperatures lower arousal (the state of activation of an individual), decreasing children's attention and affecting timing and choice of behavior (Pawel Wargocki & Wyon, p. 361, 2016; Willem, 2006).

However there is little understanding of what are comfortable conditions for children, since all current standard criteria, e.g., (ASHRAE–55, 2017; EN15251, 2007; ISO 7730, 2005) for the evaluation of thermal comfort are based on studies on adults.

As evidenced from the literature, there is a significant need for research studies that can contribute to a better understanding of how to provide a comfortable indoor environment for school children. There are few thermal comfort field studies that include students aged 10–14 years old, from primary school level. There are even fewer studies that include perceptions of students and teachers on thermal comfort and indoor air quality through survey questionnaires designed for their age group. This study will contribute significantly to knowledge in this area.

Additionally, there is a dearth of studies performed in developing countries from South America, with different climate and cultural backgrounds, like Chile, where there is no legislation for indoor environmental quality standards. Furthermore, cities in the southern part of Chile have high outdoor air pollution that occurs during winter due to wood-burning heating systems. The latter has more significant implications because most school designs in Chile are naturally ventilated buildings, where operable windows, doors, or envelope filtrations are the only means of fresh air ventilation and minimal provision of heating systems. A deeper understanding of the physical conditions of classroom environments across different school types (public, private–subsidized, and private non–subsidized) and the level of air pollutant concentrations students and teachers are exposed to is sorely needed.

This study will shed light on these issues as well as assist in the design process and operations of schools. Additionally, it can inform teachers and parents about adaptive strategies, and school administrators and policymakers about the decision-making of new policies, and eventually educate lawmakers for ordinances that can improve IEQ.

1.6. Scope & Limitations

Scope:

The scope of this study encompasses field measurements of physical conditions of IEQ in classroom with subjective responses through survey questionnaires. Specifically, the study evaluates thermal comfort and indoor air quality parameters (e.g., air temperature, relative humidity, air velocity, radiant temperature, CO_2 and particulate matter $PM_{2.5}$, PM_{10}) of middle school classroom grade levels (6th to 8th grade).

Subjective responses included: 1) "right–here–right–now" type of questions on current status of thermal comfort, air movement, and air quality using multiple voting scales; 2) general personal satisfaction and perception about home and classroom environmental conditions, and health-related symptoms experienced in the past; 3) house conditions; 4) personal perception of impacts of classroom environmental parameters on class work; and 5) general demographic information, gender, age, nationality, and anthropometrics of height and weight were collected.

Limitations:

This study acknowledges the importance of studying the effects and relationships between poor air quality on performance and health-related symptoms, on students and teachers in classroom environments — for example, the effects of CO_2 concentrations on absenteeism, and health symptoms. However, this study did not include such evaluations of the effects of thermal and air quality comfort on students' and teachers' performance and health.

The original design for this study included measurements of two distinct temperature regimes (i.e., summer and winter season). However, due to a delay in the import of fieldwork equipment, the start of data collection was delayed a month from what was initially anticipated. Because of this delay, it was only possible to collect measurements during fall (a transitional season) and winter season.

Additionally, this delay affected the schedule planning for the second field campaign during winter, affecting the sample size for this assessment. Therefore, it was only possible to assess four school buildings instead of the original nine from the first field campaign because of the winter break holiday schedule of schools.

During fieldwork assessment in the fall season, measurements evidenced a variation of the daily mean outdoor temperature, showing a difference of 6.4ºC between the highest outdoor daily mean temperature value measured at the beginning of the field study (April 23rd) and the lowest outdoor daily mean temperature value at the end of the campaign (May 30th), as seen in Table 5.5. This unfortunately influences the calculation for comfort temperatures by being outside of the comfort range permissible by the adaptive model in (ASHRAE–55, 2017) standard. The range allowed for prevailing mean outdoor temperatures is >10ºC and < 33.5ºC.

Although these limitations can have an impact on the accuracy of the results, the methodology and data analysis have accounted for such variations of these unexpected events.

1.7. Organization of the Dissertation

The dissertation is organized in a series of chapters that explores the different topics related to the study aims. This dissertation includes previously published and unpublished co-authored material. Committee members have contributed to these papers, hence they are listed as co–authors. The following outlines the main topics and research questions addressed by each chapter.

Chapter 1: introduces the research topic and research problem, structure, and significance of the research. It states the research aims, questions, scope and its limitations, and outlines the research design and approaches for the development of this thesis.

Chapter 2: provides background information of definitions of thermal comfort and indoor air quality parameters, approaches commonly used in the literature to evaluate thermal comfort and air quality, and international standards.

Chapter 3: provides a literature review on current research on comfort and indoor air quality of school fieldwork studies carried out internationally as well as locally in Chile, and research studies on effects of temperature and air quality on students' health and performance.

Chapter 4: seeks to answer the first and third research questions of the thesis. This chapter presents results of previously published co-authored material from the conference proceeding for the Architectural Research Centers Consortium (ARCC) 2019 International Conference: Future Praxis Applied Research as a Bridge Between Theory and Practice.

Chapter 5: seeks to answer questions two and four of the thesis. This chapter presents the results of an unpublished article that is planned to be submitted to the international journal Building and the Environments.

Chapter 6: conclusions and future work

CHAPTER II:

BACKGROUND

2.1. Indoor Environment

Providing a good indoor environment is essential for the success of building design, not only because it is seeking occupants' comfort, but also the significant impact on energy consumption and thus its influence on sustainability. Today's standards that define acceptable indoor environments should address all these factors (Nicol & Humphreys, 2002).

The indoor environment can be defined as dynamic interactions of spatial, social, and physical factors which affect productivity, health, and comfort (Clements-Croome, 2018). The condition of comfort in an environment "is the result of the interaction of physical exchanges, physiological, psychological, social and cultural rights, it depends on the architecture, the clothing, the eating, and the climate" (Fabbri, 2015, p. 8). Therefore, the assessment of Indoor Environmental Quality (IEQ hereafter) does not depend solely on the physical parameters of the environment (i.e., temperature, humidity, air velocity, acoustics, and lighting), but also the human body's physiological and psychological responses to them.

The human body, through its physiological systems, will respond to the different environmental variables through a dynamic interaction, which can result in successful or unsuccessful response to the outside world. Unsuccessful responses can lead to death, due to conditions beyond survivable limits, whereas our goal is the successful response of the body as it uses its resources to maintain an optimum state. The assessment of comfort in an indoor environment, which can help us make the judgment of the conditions of well-being, comes under four categories: 1) Thermal Comfort, 2) Indoor Air Quality, 3) Lighting Comfort, and 4) Acoustic Comfort. Thermal environment can help determine if a person is too hot, too cold or in thermal comfort (Parsons, 2003). Evidence has shown, that human beings react differently to the indoor environment, for example, children in school versus adults in office settings. Children move around into different classroom spaces during a school day and have different activities that can change their metabolic rate and therefore, their thermal perception (Havenith, 2007; Kim & de Dear, 2018b). On the other hand, adults in an office are mostly sitting in the same space and performing similar 3working activities resulting in a long-term sedentary position.

Parsons, in 2003 noted that, there are four principal methods that can assess human responses to the environment: 1) Subjective Methods; 2) Objective Measures; 3) Behavioral Methods, and 4) Modeling Methods. This study addresses children/teachers' interaction with classroom environments, through the first two methods via fieldwork data collection.

The following chapter focuses on the contributions of past field studies of thermal comfort and indoor air quality, and the applicability of the adaptive model in school settings. The literature background is divided into four main sections: 1) definitions of comfort and parameters, 2) models of thermal comfort, 3) international standards, and 4) studies on thermal comfort and indoor air quality in school settings.

2.2. Defining the Meaning of Thermal Comfort and Indoor Air Quality

Thermal comfort is linked to how our bodies need to maintain a constant internal temperature (balance of heat), and it depends on the environment we are in or the amount of heat we produce. This internal temperature of our bodies is maintained in the range of 37 °C when conditions allow our human body to achieve a temperature balance with the environment, which is vital for our health and well-being (Nicol, Humphreys and Roaf, 2012). The thermal interaction between the human body and the environment in maintaining this stability is a process that Nicol et al., (2012), called "thermoregulation", which is complex and involves research on multiple disciplines such as psychology, physiology, physics, and sociology. Nicol et al., (2012), describe that sociologists analyze the way occupants react to the environment, physiologists study how we use and produce heat, and psychologists interpret conscious feeling about the environment. On the other hand, design builders should consider all of these factors by providing a design that best meets occupants' comfort needs. For example, thermal comfort standards can help architects, engineers, and building constructors design buildings that can provide an indoor environment that more than 80% of their occupants will find thermally comfortable, which is an overall acceptability specified in many standards such as ASHRAE-55 (2017). However, the dissatisfaction of the remaining 20% raises the question: are we supposed to ignore their discomfort? (ASHRAE–55, 2017)

Researchers have provided multiple definitions of thermal comfort in the literature. In the field of architecture, Olgyay (1953) was probably the first to formalize the concept of thermal comfort through his bioclimatic approach (as cited in Shamila Haddad, 2016, p. 16). Lisa Heschong's Thermal Delight in Architecture (Heschong, 1979), describes that there is an underlying assumption that the best thermal environment is the one that goes unnoticed and that once objectively "comfortable" all of our thermal needs have been met. Heschong notes this is the ideal approach by the heating and cooling engineers:

> "The steady-state approach to the thermal environment assumes that any degree of thermal stress is undesirable" (Heschong, 1979, p. 21).

Benzinger (1979) and Hensen (1991) agrees with this assumption of what thermal comfort should be, by describing it as:

> "a state in which there are no driving impulses to correct the environment by behavior."

The ideal approach imposed by engineers that Heschong describes, is the concept of uniformity or static conditions, providing the same temperature across multiple spaces within a building, which in turn requires a great effort and energy for engineers to maintain. These static conditions are utterly unnatural to what happens outdoors or in naturally-ventilated spaces in which physical variations occur. Heschong argues:

> "When thermal comfort is a constant condition, constant in both space and time, it becomes so abstract that it loses its potential to focus affection" (Heschong, 1979, p. 36)

It has been assumed that providing a constant temperature can prevent people from being distracted or making adjustments to the internal conditions to reach a comfortable thermal state. However, studies have shown that people seemed to enjoy a range of temperatures, "in spite of extra physiological effort required to adjust to thermal stimuli" (Heschong, 1979, p. 21). Providing a fixed set temperature, particularly in indoor environments that are naturally ventilated, many times is not a possible solution for occupants. There is an underlying notion, as noted by Fitch (1972) that humans might subconsciously need thermal variations (Spengler, McCarthy, & Samet, Chapter 15, 2001). Heschong (1979) suggests that we should look for more than just a simple comfort in a building, but through our thermal sense we can not only find satisfaction but under certain conditions, we can produce delight.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE hereafter) provides the definition that is most accepted for the thermal comfort, which defines it as:

> “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ANSI/ASHRAE 55, 2017, p. 3).

This definition leaves open what is meant by "condition of mind" or "satisfaction," but it does emphasize that judgment of comfort is a cognitive process which involves different interactions influenced by physical exchanges, physiological, psychological, and other processes (ASHRAE Hanbook, 2017). Comfort also depends on behaviors that are consciously or unconsciously guided by thermal and moisture sensations to reduce discomfort. Examples of such adaptive behaviors include: altering clothing, opening a window, changing posture or location, changing thermostat settings, or leaving the space (ASHRAE Hanbook, 2017). The purpose behind the science of thermal comfort is to provide user satisfaction, health, delight, and energy conservation strategies as noted by Nicol, Humphreys, and Roaf (Nicol, Humphreys, & Roaf, 2012).

Indoor Air Quality (IAQ hereafter), refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants (EPA, 2019). Understanding and controlling common pollutants found indoors can help us reduce the risk of indoor health concerns.

In “Building Breathing Space” by Steven Connor (Academie, 2006, Chapter 2, p. 118), the author describes that "buildings sweat, age, excrete and they respire." Research studies have helped us understand that one of the significant concerns of indoor air quality is the off-gassing of building materials, in addition to occupant odors as well as occupant breathing (Passe & Battaglia, 2015). Therefore, ventilation is required to adjust humidity levels as a result of exhaled air by occupants or interior conditions, as well as, to remove excess heat, body odors, and materials' emissions (e.g., volatile organic compounds, VOC), which are major health concerns. As described by Passe & Battaglia (2015), ventilation has two primary goals. First, to provide cooling air through the reduction of temperature or cooling by evaporation through the increase of air velocity. Second, to maintain air exchange rates that can help keep a proper composition of air, by avoiding stale or nauseating conditions, due to little oxygen or to many pollutants such as VOC, or CO_2. As addressed by Olli Seppänen (Seppänen, 2006), ventilation and natural ventilation can help remove or dilute pollutants that can cause health-related issues such as (in Santamouris & Wouters, 2006, Chapter 9, p. 247 as presented in Passe & Battaglia (2015) :

1. Infectious diseases caused by airborne viruses or bacteria;
2. Growth of microorganisms in humid air, for example, mold within the building envelope construction
3. Allergies and asthma caused by exposure to mold that thrives at high humidity indoors;
4. Lung cancer caused by exposure to tobacco smoke and radon decay products;
5. Cancer and skin irritation as well as allergies caused by VOCs and formaldehyde in the air
6. Dizziness and nausea caused by odors, which can lead to dissatisfaction with the indoor environment;

7. Sick building syndrome (SBS).

Indoor humidity is considered a widespread cause of respiratory diseases among children, due to the fact that high indoor air humidity promotes mold growth. Particular care must be taken in high-density classroom environments, and leaky building envelopes, which can lead to internal condensation on walls and colder surfaces. Therefore, the removal of humidity through ventilation is of great importance to reduce health-related risk due to mold growth. On the other hand, if too much humidity is removed other detrimental problems like respiratory issues can be created due to the dry air (Passe & Battaglia, 2015). Careful consideration needs to be taken for the appropriate ventilation rates to provide a healthy environment. This topic is still debatable today in terms of energy savings, and the type of equipment required to condition the air.

2.3. Thermal Comfort and Indoor Air Quality Parameters

Providing comfortable conditions depends on factors that affect occupants' perception and experience of thermal comfort. Currently, indoor thermal comfort is influenced by four parameters of the thermal environment, including air temperature, relative humidity, mean radiant temperature (i.e., the temperature of surrounding surfaces), and air velocity. Additionally, these parameters are combined with two personal factors: clothing (i.e., thermal resistance) and activity level (i.e., metabolic rate) of occupants. It is also important to consider temperature stratification and the temperature difference over the entire body, and surface temperatures of adjacent walls near the occupant, which can have an impact on the perception of comfort. Human beings react differently to comfortable conditions due to psychological and physiological factors, which makes it difficult to satisfy everyone.

In school settings, the temperature is considered to be one of the most important indoor environmental parameters, as higher temperatures can negatively impact performance (Pawel Wargocki & Wyon, 2007).

On the other hand, for IAQ, one of the "most important validation parameters (next to temperature and humidity)" is air change rates for ventilation strategies (Passe & Battaglia, 2015, p.62). However, providing a ventilation strategy can only be implemented in a continuous mode of air change rate in naturally-ventilated buildings. Therefore, the rate in question becomes the minimum rate for natural ventilation strategy, which is driven by dynamic and not continuous homogeneous forces (Passe & Battaglia, 2015, p.62). Ventilation rates that provide healthy IAQ are determined by the following factors: the number of people occupying the space, their activity level, the volume, and the area of the space. In recent findings, little evidence exists that supports the tenet that higher ventilation rates [2.5 versus 26 cfm (1.2 versus 12.3 L/s) per person as evidenced in Seppanen, Fisk, and Mendell, (1999)] provide healthier indoor environments (Holladay, M. 2013, as cited in Passe & Battaglia, 2015). However, the perception of air quality and ventilation rates have shown a connection in studies by Seppänen et al., (1999) and also have been correlated with performance by Wargocki et al., (Pawel Wargocki, Wyon, Sundell, Clausen, & Fanger, 2000).

Other IAQ parameters are PM2.5 and PM10, that refer to particulate matter with particle diameters up to 2.5 µm and 10 µm, respectively, and are amongst the most hazardous of air pollutants for human health. Smaller particles < 2.5 µm are the most harmful because they penetrate deep into the lungs and are difficult to remove from the air (Santamouris & Wouters, 2006, p. 254). These types of particles can cause various health-related issues, such as cardiovascular diseases or asthma attacks due to pollen or airborne dust. Carbon dioxide (CO_2) is also an essential parameter of IAQ and can be an indicator of other pollutants in the air and for ventilation rates. CO_2 concentrations depend on occupancy, ventilation rate, and room volume (Santamouris & Wouters, 2006, p. 256).

School environments, in general, tend to be particularly highly polluted due to the following reasons: crowded classrooms, low ventilation rates, multiple activities that can increase children's metabolic rate and indoor temperature, inadequacy in providing fresh air, bringing pollutants in from the outdoors after break times, or due to inappropriate selection for site location; e.g. near heavy-traffic streets or highways as evidenced in the literature review studies (Chatzidiakou, Mumovic, & Summerfield, 2012; W. J. Fisk, 2017). Further careful consideration of these IAQ parameters and their effect on health, comfort, and performance of children and possible negative impacts is required.

2.4. Research on Thermal Comfort

An extensive volume of research, based on studies on adults in office settings, has focused on defining commonly accepted criteria and parameters of thermal comfort that have been distilled into different international standards. In the USA, thermal comfort considerations are guided by ASHRAE standard 55, in the UK by CIBSE, and in Europe by standard EN ISO 7730 (ASHRAE–55, 2017; CIBSE, 2006; ISO 7730, 2005). Over the last 50 years, two distinct research methodologies have been used for evaluating indoor thermal comfort and the interaction between the human body and the surrounding environment based on questionnaire surveys: 1) laboratory-based studies (climate chambers) and 2) field-based studies (real-world settings).

Climate chamber studies are based on the theory of the heat balance of the human body, in which thermal comfort can be achieved through strictly controlled conditions of the building's indoor climate engineering systems (e.g., air-conditioned) (Richard. de Dear, 2004; Halawa & Van Hoof, 2012). In these settings as de Dear describes, occupants are "passive thermal comfort sensors," occupants are not expected to change or intervene, and there is a specific expectation of what the environmental conditions should be, and any departure from that would be evaluated as unfavorably (de Dear, 2004, p. 33).

Instead, **field-based studies** rely on thermal comfort sensations of occupants measured in situ (i.e., while they are doing their daily activities) together with simultaneous physical measurements of the environment. In these real settings, a holistic person-environment systems approach in which the occupant is an active agent, or interactive with the building, informs by implementing adaptive opportunities available to create a thermally comfortable indoor environment for themselves combined with controlled conditions of the building's indoor climate (de Dear, 2004).

2.5. Models Thermal Comfort

From these two research methodologies, two main model approaches of thermal comfort have been developed and adopted in international standards: 1) the heat-balance model (Fanger, 1970), and 2) the adaptive comfort model (de Dear, 1998; Humphreys & Nicol, 2002a). The latter has been incorporated only sparingly over the last decade.

The two models use very different algorithms for calculating comfort zone prescriptions, but also differ significantly about the way buildings are designed and how the environments are controlled (Spengler et al., 2001, p. 15.12). One of the most relevant differences between models is their potential for energy savings in todays' buildings and the impacts of greenhouse emissions on climate change.

2.5.1. The Heat Balance or Steady-State (Rational) Model

The heat balance model, for calculating the steady state of thermal comfort, is the result from an extensive research done inside air-conditioned climate chambers developed by Ole Fanger's research team in the 1960s and 1970s. In this model, thermal comfort can be reached when the heat balance of the body is neutral, that is, there is a balance between heat production and heat dissipation, as seen in the following equation 2.1 (Fanger, 1970, p. 22).

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \qquad (2.1)$$

Where:

H = the internal heat production in the human body

E_d = the heat loss by water vapor diffusion through the skin

E_{sw} = the heat loss by evaporation of sweat from the surfaces of the skin

E_{re} = the latent respiration heat loss

L = the dry respiration heat loss

K = the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)
R = the heat loss by radiation from the outer surface of the clothed body
C = the heat loss by convection from the outer surface of the clothed body

Based on thermoregulation and heat balance theories, the human body employs physiological processes (e.g., sweating, shivering, regulating blood flow to the skin) in order to reach that thermal balance (Charles K. E, 2003, p. 5). Humans gain heat from metabolism and often from the surrounding environment, and they release heat through convection, radiation, evaporation, and conduction. Humans cannot tolerate a wide range of core temperatures, as cold-blooded reptiles do, so in a short period, heat gains must be balanced with heat losses (Spengler et al., Chapter 15, 2001). In the heat balance or static model of thermal comfort, the model views occupants as passive recipients of thermal stimuli, and the effects of a given thermal environment are mediated exclusively by the physics of heat transfer of their bodies and automatic physiological responses (de Dear & Brager, 1998).

Using the heat balance equation (2.6.1), Fanger obtained the comfort equation by inserting comfort expressions for skin temperature and sweat rates from experiments by using American college-aged persons exposed to an environment under steady conditions (Fanger, 1970, p. 42). The comfort equation included four environmental parameters and two personal factors (as mentioned in section 2.4). Thus, combining these parameters would create optimal thermal comfort for occupants under steady state conditions. However, this equation does not take into account people's thermal sensation, which does not satisfy the equation (Shamila Haddad, 2016). Therefore, Fanger did further studies in which he asked people about their thermal sensation at different temperature conditions in controlled environments.

In these studies, participants, mostly male adults wearing office garments, were exposed to various thermal conditions while performing standardized office activities. The researchers chose physical conditions while thermal responses were collected from subjects by asking their thermal sensation vote (TSV) on a psycho-physical ASHRAE seven-point scale, as seen in Table 2.1. In other studies, subjects were able to adjust the thermal environment themselves, adjusting the temperature until they felt thermally 'neutral' (i.e., neither hot nor cold, voting 0 on the scale) (Charles, 2003, p. 5).

Table 2.1. ASHRAE thermal sensation scale (ASHRAE55, 2017)

Thermal sensation descriptor	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Point scale	-3	-2	-1	0	1	2	3

The aim of Fanger’s model was to predict the mean thermal sensation vote of a group of people and their respective percentage of dissatisfaction with their thermal environment through the use of indices such as: 1) the Predicted Mean Vote Index (PMV), and 2) the Percentage of Dissatisfaction Index (PPD) (Rupp, Vásquez, & Lamberts, 2015). The PMV index is calculated through the four parameters of the thermal environment (air temperature, mean radiant temperature, air velocity, and humidity) and with two personal variables (metabolic rate and clothing insulation) that influence on thermal comfort. Therefore, the PMV index predicts the mean thermal sensation vote of a group (on ASHRAE seven-point scale) of people at any given combination of the four environmental parameters and the physical activity and clothing worn by occupants. According to Fanger (1970), dissatisfied votes are those that fall within -2 (cool), -3 (cold), + 2 (warm), or +3 (hot), while comfortable votes are within -1 (slightly cool), 0 (neutral), and +1 (slightly warm) on the ASHRAE scale.

Calculating these indices are complicated, and their calculation by hand is hardly possible, as seen in ISO 7730. Therefore, computer code programs (Schweiker, 2016), datalogger instruments with built-in software (e.g., Testo 480) or web application tools for ASHRAE 55 (Schiavon, Hoyt, & Piccioli, 2014) are used to calculate PMV-PPD indices. For these applications, indices can be calculated as a function of metabolic rate (W/m^2), clothing insulation (clo), air temperature (°C), mean radiant temperature (°C), relative humidity (%), and air velocity (m/s). For input quantities for clothing insulation or metabolic rate, values are obtained from different standards such as ASHRAE–55, 2017; ISO 7730, 2005; ISO 8996, 2004. The PMV method is the basis of international standards that are still currently used today, such as EN15251, 2007; ISO 7730, 2005; and ASHRAE–55, 2017.

Due to the nature of PMV studies (i.e., based on laboratories), numerous studies have investigated the appropriateness of heat balance indices in real-world situations and have questioned its validity. Field studies of thermal comfort are conducted in actual buildings under normal conditions of occupancy, and many times involved a much larger sample size with "real" occupants as opposed to "paid college-age subjects" (de Dear, 2004). As noted in Nicol et al., (2012, p. 49), the model is unable to take into account the social and climatic factors that exist in real-world field surveys. Humphreys and Nicol

(2002a) argue that exposure to a large group of people to a single thermal space, wearing the same clothing insulation, and having the same level of activity rarely occurs in real-world settings. Additionally, the applicability and validity of the whole index in other geographic contexts, different types of buildings, and model input parameters such as clothing and metabolic rate, have also been questioned in multiple studies, arguing that a single model cannot be applicable to different settings (Halawa & Van Hoof, 2012; Van Hoof, Mitja Mazej, 2010; Humphreys & Nicol, 2002; Van Hoof, 2008).

Studies have also shown that PMV differs from an occupant's vote, particularly in naturally ventilated spaces in which the range that occupants find comfortable in field studies is much broader than the steady-state model allows (De Dear & Brager, 2002; Humphreys & Nicol, 2002). The latter has been the subject of intensive research in field studies, in which the differences can be explained by the concept of "behavioral adaptation," i.e., adjustment to climatic conditions in which the field studies took place. This has led to the adaptive model described below.

2.5.2. Adaptive Comfort Model

Looking at climate in addition to thermoregulatory responses, the adaptive model takes into account a range of responses (i.e., behavioral, physiological, and psychological adjustments) that occupants might take in order to achieve thermal comfort (Spengler et al., Chapter 15, 2001). These adaptations are not considered in the heat balance model as occupants are viewed as "passive recipients" of thermal stimuli as noted by de Dear (2004). Instead, in the adaptive model occupants are active agents of their thermal environment. The underlying principle of the adaptive model as described by Humphreys and Nicol:

> "If a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort" (Humphreys, Nicol, 1998).

The adaptive principle sees occupants as active participants in making adjustments to their environment, e.g., opening windows, changing the thermostat or making adjustments to themselves, i.e., adding or removing clothing, changing posture in a process of dynamic equilibrium with the thermal environment. In contrast to the climate chamber approach, in which indoor conditions are controlled for research, the adaptive model relies on field studies in which thermal sensation votes of occupants were collected in situ while they were doing their routine activities (de Dear, 2004) in order to evaluate existing conditions that occupants are exposed to.

The origins of the adaptive model are based on field studies in naturally ventilated buildings by Nicol and Humphreys (Humphreys, Nicol, 1998; 2002a; 2010), Auliciems (Auliciems, 1981), and de Dear, Brager, and Cooper (de Dear, Brager, & Cooper, 1997; de Dear & Brager, 1998). From these field studies, relationships between indoor operative temperatures (acceptable ranges) and prevailing outdoor air temperatures were determined through linear regressions such that higher outdoor temperatures allow for higher indoor temperatures (Rupp et al., 2015), thus, ultimately shifting the paradigm of Fanger's theories and steady–state model. Additionally, the adaptive model considers contextual factors and past thermal history, which can influence occupants' thermal expectations and preferences (de Dear & Brager, 1998). People who live in warm climates would prefer and tolerate higher indoor temperatures, in contrast to people in cold climate zones who would prefer and tolerate lower indoor temperatures, which is the opposite assumption underlying the PMV-model. As noted by de Dear, "the context of a person-environment interaction includes not just environmental context but also cognitive and even emotional context" (de Dear, 2004).

Human thermal adaptation can be classified into three categories as described in de Dear and Brager (de Dear & Brager, 1998) and referenced by other authors (Rupp et al., 2015; Spengler et al., 2001): 1) behavioral adjustment; 2) physiological; and 3) psychological.

1) **Behavioral adjustment:** includes all modifications a person might do consciously or unconsciously, to achieve thermal comfort. These adjustments can be classified into personal (e.g., adding or removing a clothing item), environmental (e.g., turning on an air conditioning/heater, opening a window), and cultural responses (e.g., having a siesta in the heat of the day, or drinking hot liquids like "mate" in cold days).
2) **Physiological adaptation:** the body's acclimatization for long-term exposure to thermally stressful environments (hot or cold). Physiological adaptations are changes in the internal settings at which thermoregulatory response occur, such as shivering, sweating, vasodilation, and vasoconstriction. Physiological adaptations can be divided into genetic (intergenerational) adaptation and climatization (within the individual's lifetime)
3) **Psychological adaptation:** are complex combinations of factors outside the realm of thermal environmental parameters. Thermal perceptions might be directly and significantly attenuated by one's past thermal experiences and

expectations of what buildings offer in terms of architectural design and technological features of environmental control systems (e.g., HVAC).

In field studies of the adaptive model, particularly in naturally ventilated buildings, occupants are more aware of outdoor weather conditions than in centrally-controlled HVAC buildings. Windows provide a strong link between indoor and outdoor conditions. By using the ASHRAE RP-884 database de Dear, Brager and Cooper (de Dear & Brager, 1998; de Dear et al., 1997; de Dear & Brager, 2002), found an agreement between comfort temperature (preferred indoor temperatures) in HVAC buildings and the predicted temperature of PMV. On other hand, in naturally ventilated buildings, the same conclusion could not be drawn; the PMV model was not able to predict the broader range of temperatures that occupants preferred as seen in Figure 2.1. In such buildings, occupants seem capable to adapt to a much wider range of conditions and accept higher indoor temperatures than predicted by PMV-PPD models (Richard. de Dear, 2004). According to de Dear and Brager, the PMV model is not applicable in naturally ventilated buildings, because the model only partially accounts for thermal adaptation to the indoor environment.

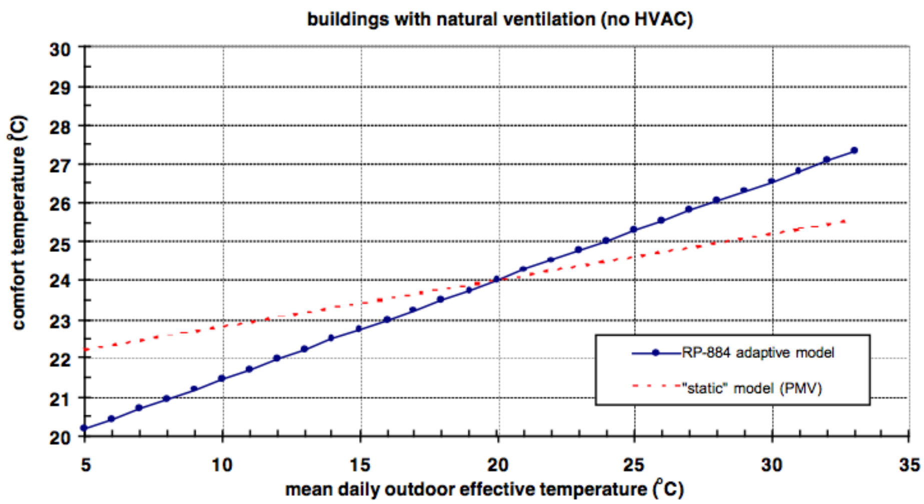


Figure 2.1: Comparison between the adaptive model and the "static" model (based on PMV predictions) applied to naturally ventilated buildings, from the data based off RP-884, source (de Dear et al., 1997)

The adaptive model, from field studies research, has shown strengths and weaknesses that are worthy of noting. The model provides an opportunity that can be translated into energy savings, due to the broader ranges of acceptable conditions in naturally ventilated buildings which allows for higher acceptable operative temperature as the outdoor temperatures increase (de Dear & Brager, 1998). The reason behind this is due to the higher levels of personal control occupants have in these buildings, thanks to design opportunities for access to operable windows (de Dear et al., 2013). The notion of energy savings is also pointed out by Nicol and Humphreys (Nicol & Humphreys, 2009): the adaptive approach provides an opportunity for comfort in buildings which can also be compatible for low-carbon buildings. The latter, however, requires buildings to offer the ability for more active occupants through integrated design that can maximize the use of passive architectural strategies which can reduce its dependence on mechanical control systems for heating/cooling.

Despite the strengths of the adaptive model, weaknesses have been identified by researchers. Due to the nature of the statistical analysis of the adaptive approach, it is difficult to generalize the results from one survey to those from another survey even when the conditions are similar (Humphreys & Nicol, 2002a). Another criticism is this notion that the model is a "black box" based on empirical observations due to the interpretation that the adaptive mechanisms are hidden, not fully defined, and not quantified or related to measurements (Nicol, Humphreys, & Roaf, 2012, p. 30). However, as noted in Nicol et al., (2012) one way to address this criticism is by developing models of usage patterns of occupants' individual adaptation mechanisms (i.e., opening windows, turning on a fan, pulling down blinds, or turning on the heat) that can occur inside buildings. The following work by Fergus Nicol, Humphreys, & Olesen, 2004; Yun & Steemers, 2007; and Rijal, Tuohy, Humphreys, Nicol, 2012 have developed such models and algorithms. However, such predictions of adaptive behaviors and usage are hard to predict and generalize, due to the particular nature of different building types, social context, and occupants' expectations. More research is required in this area.

Finally, the model also has been scrutinized by its simple approach of only considering operative temperature to calculate the comfort temperatures based on outdoor temperatures, and by overlooking the environmental and personal parameters which have influenced PMV (Toftum & Ole Fanger, 2002). The latter has been raised by Humphreys and Nicol (Humphreys & Nicol, 2002b) and de Dear et al., (2013) by arguing that comfort temperatures are clearly a function of more than just outdoor temperatures, people’s clothing, or building controls; they are dependent on outdoor conditions, like outdoor temperature. Therefore, there is feedback between climate and adaptive actions, which translates to only considering outdoor temperature for real situations like free-running buildings (Humphreys & Nicol, 2002a). Air temperature or operative temperature are sufficient indices for thermal comfort and including other variables can create biases in the assessment of thermal environment, as noted by Humphreys and Nicol. However, it is not clear what biases Humphreys refers to or how they can impact the overall adaptive thermal comfort.

The adaptive model has also ignored the effects of humidity and air movement on comfort, which were not captured in the ASHRAE-55-2004 standard version and only in the recent revision of ASHRAE 55-2010, which incorporated air movement as a way to stretch the warmer comfort zone, from 0.8 m/s to 1.2m/s. This change came after more than 20 years of supporting evidence that more air movement can allow comfort at higher indoor temperatures (de Dear et al., 2013). On the other hand, in cold climate zones, the use of more clothing insulation has not been acknowledged as a way to broaden the comfort zone towards a colder side (< 10°C) and potentially reducing energy use through heating. Further studies are necessary to look at this alternative for cold climates where occupants can be more adaptive to cold temperatures. Even though the model presents limitations and has been subject to scrutiny, its incorporation in international standards is a significant step forward in recognizing the vital role occupants exert on their indoor environment.

2.6. International Standards for Thermal Comfort

Currently, there are three well-known and widely used international standards: ASHRAE Standard 55 (2017), ISO Standard 7730 (2005), and CEN Standard EN15251

(2007). These standards are used to determine design values for operative temperature, and comfort equations based on the steady-state heat balance or the adaptive thermal comfort models, as seen in Table 2.2.

Table 2.2. Thermal comfort standards in applicable to classroom spaces

Standard	**Thermal comfort approach**	**Operative temperature range (°C)**		**Clothing insulation**	
		Winter	Summer	Winter	Summer
ISO 7730 (2005)	heat balance/steady-state				
	–0.5<PMV<+0.5 PPD < 10%	22.0 ± 2.0	24.5 ± 1.5	1.0 clo	0.5 clo
ASHRAE 55 (2017)	heat balance/steady-state				
	–0.5<PMV<+0.5 PPD < 10%			1.0 clo	0.5 clo
	Adaptive				
		$T_{comf} = 0.31\ T_{pma(out)} + 17.8$ 90% accept.: ± 2.5 80% accept.: ± 3.5		1.0 clo	0.5 clo
EN 15251 (2007)	heat balance/steady-state				
	–0.5<PMV<+0.5 PPD < 10%			1.0 clo	0.5 clo
	Adaptive	$T_{comf} = 0.33\ T_{rm} + 18.8$			

Source: ASHRAE Standard 55 (2017), ISO Standard 7730 (2005), and CEN Standard EN15251 (2007)

Some standards provide thermal comfort ranges under three types of categories for indoor environments, as well as, centrally controlled HVAC, naturally ventilated, free-running buildings (neither heated nor cooled mechanically). Classroom spaces are considered in the second category under standard ISO 7730 and EN15251. In ASHRAE-55 all spaces are considered within the following criteria: occupants have an activity level that results in a metabolic rate between 1.0 and 2.0 Met. No standard addresses children's age groups. The latter has been criticized by many studies (Kwok, 1997; Shamila Haddad, 2016; Rupp et al., 2015; Teli, 2013) for the lack of applicability of such standards in classroom settings.

2.6.1. ASHRAE 55-2017: Thermal Environmental Conditions of Human Occupancy

The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) has sponsored and developed an international standard to establish criteria for thermal comfort. As stated in ASHRAE-55 2017 (p.2):

> "the purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space."

The ASHRAE-55 Standard was the first international standard to incorporate the adaptive model for naturally conditioned spaces in 2004, this after the findings of the project RP-884 based on the work of de Dear and Brager (de Dear & Brager, 1998; de Dear & Brager, 2002; de Dear, 1998). The RP-884 project was a large sample of quality-assured field data across major climate zones of the world, as noted by de Dear. Because the data came from independent surveys, de Dear and Brager categorized the studies into three types of classes (I, II, III) based on their quality of instrumentation and assessment procedures. Class I had the most rigorous requirements.

The principal means to achieve adaptive control of indoor temperature is through the use of operable windows and cannot be applicable for buildings that have a cooling system (e.g., refrigerated air conditioning, radiant cooling, or desiccant cooling) or heating system in operation. However, mechanical ventilation with unconditioned air can be utilized. Occupants are free to adapt by changing their clothing for at least as wide a range as 0.5 to 1.0 clo. (ASHRAE, 2017).

The adaptive standard defines upper and lower limits of a comfort zone in which occupants would expect to find 80% acceptability (T_{comf} ±3.5°C) and 90% acceptability (T_{comf} ±2.5°C), the latter is for a higher standard of thermal comfort as Figure 2.2. It also provides a thermal comfort model equation (Eq. 2.2), developed from the results of statistically significant linear regression analysis of RP-884 project database from approximately 9,000 naturally ventilated buildings (de Dear et al., 2013):

$$T_{comf}=0.31T_{pma(out)}+17.8 \qquad \text{(Eq. 2.2)}$$

where T_{comf} is the optimal temperature for comfort and $T_{pma(out)}$ is the prevailing mean outdoor temperature. The model is used when prevailing mean outdoor temperatures range from 10°C to 33.5°C.

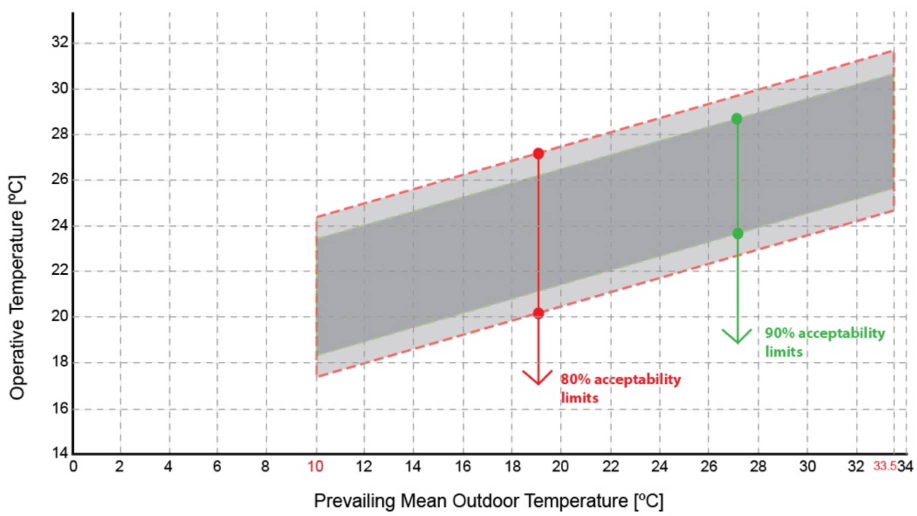


Figure 2.2 Adaptive comfort zone chart. Acceptable operative temperature ranges for 90% and 80% for naturally conditioned spaces, adapted from (ASHRAE55, 2017)

$T_{pma(out)}$ originally was defined as the prevailing mean monthly outdoor air temperature for the month in question (ASHRAE, 2004) to facilitate its adoption more easily by practitioners than the daily mean outdoor temperature (de Dear & Brager, 2002). This has been changed in the standard since 2013, after the studies of Humphreys and Nicol in which this method has been argued that a monthly mean is very insensitive to the variability of the weather from day to day, which can impact thermal sensation based on thermal historical adaptation (Humphreys & Nicol, 2002a; Nicol et al., 2012). Implementing a method of an exponential weighting, as seen in equation (Eq. 2.3), outdoor mean temperature puts more weight on temperatures from days closer to the current one than those far away, as noted by Nicol and Humphrey (Nicol & Humphreys, 2010). People's responses depend heavily on their immediate thermal history, as seen in equation (Eq. 2.3). The current version of ASHRAE-2017 standard leaves this definition open to the user to resolve, depending on the local weather data available. The prevailing mean temperature can be calculated as the arithmetic mean or exponentially weighted mean from a minimum of 7 days or for a maximum of 30 sequential days prior the day in question (ASHRAE, 2017).

$$\overline{T_{pma(out)}} = (1-\alpha)[t_{e(d-1)} + \alpha\, t_{e(d-2)} + \alpha^2\, t_{e(d-3)} + \alpha^3\, t_{e(d-4)} + \ldots \qquad \text{(Eq. 2.3)}$$

where $t_{e(d-1)}$ is the daily mean outdoor temperature for the day before the day in question, and $t_{e(d-2),\ \ldots}$ is the daily mean outdoor temperature for the day before and so forth. $T_{pma(out)}$ is the exponentially weighted running mean of the outdoor temperature (ASHRAE, 2017). α is a constant between 0 and 1 that controls the speed at which the running mean responds to changes in weather (outdoor temperature). Recommended =0.8 (ASHRAE, 2017).

Additionally, the standard also includes criteria for mechanically conditioned spaces, based on PMV steady-state heat balance model. It determines the acceptable operative temperature range, which corresponds to –0.5<PMV<+0.5, and PPD <10%, as seen in Table 2.3. In contrast with EN ISO 7730 and EN 15251, there is no different level of acceptability based on building type or level of expectation. As noted by Teli, the standard does not provide recommended design values for operative temperature (Teli, 2013, p. 56). However, it does specify comfort based on sedentary or nearly sedentary activities of metabolic rates of 1.1 to 1.3 MET, and clothing insulation for summer of 0.5 clo and winter of 1.0 clo.

2.6.2. **European standard EN 1525:** Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Building Addressing Indoor Air Quality, Thermal Environment, Lighting, and Acoustics.

European Standard EN 15251, was developed in 2007 and is overseen by the Comité Européen de Normalisation (CEN) (CEN, 2007). The standard is a response to needs addressed by the European Union for standards that can support the work of Energy Performance of Buildings Directive (EPBD) (Nicol et al., 2012). It includes design considerations and metrics for a range of the indoor environment parameters such as thermal comfort, IAQ, lighting, and acoustics, which can impact energy use in buildings.

Similar to ASHRAE Standard 55, this European standard incorporates an adaptive thermal comfort model after the work of an European project named SCATs (McCartney & Nicol, 2002), who tried to replicate the work of de Dear and Brager, with a longitudinal survey of a small sample of 26 offices located only in Europe (i.e., France, Greece, Portugal, Sweden and UK) (de Dear et al., 2013). By focusing only on Europe field study data, the project intended to provide an empirical basis of a European adaptive model (EN15251, 2007) that could in turn help to reduce energy use in air-conditioned buildings (McCartney & Nicol, 2002).

Nicol and Humphreys also proposed a comfort model equation (Eq. 2.4) in EN 15251, as seen in Figure 2.3, to define acceptable values of indoor operative temperature for naturally ventilated buildings, after the results of linear regression analysis.

$$T_{comf} = 0.33T_{rm}+18.8 \qquad \text{(Eq. 2.4)}$$

Where T_{comf} is the optimal temperature for comfort and T_{rm} is the exponentially weighted running mean of the daily mean outdoor temperature, as seen in Eq. 2.3. The latter is a more suitable metric for daily mean outdoor temperature, as explained above in section 2.7.1 (McCartney & Nicol, 2002).

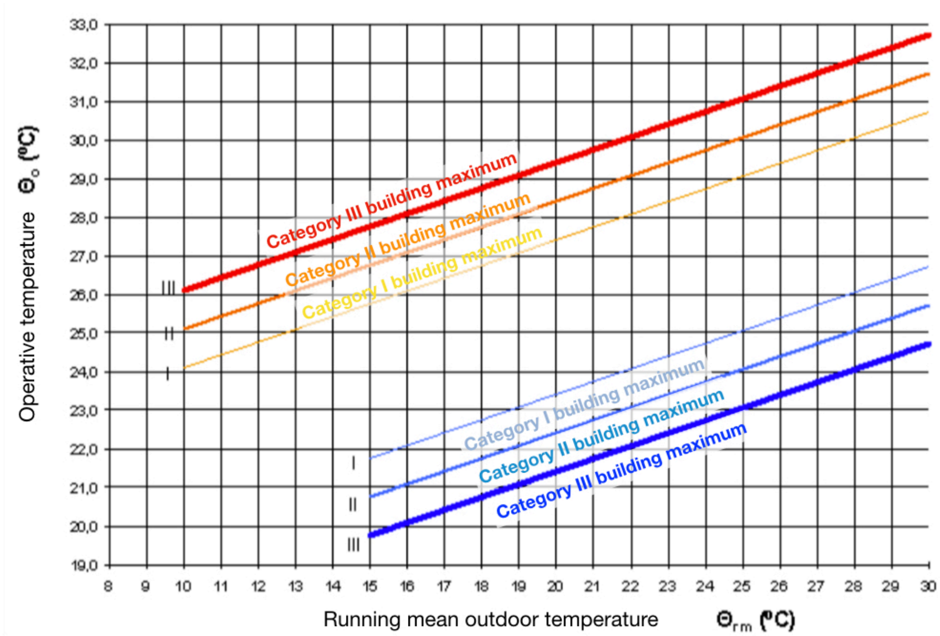


Figure 2.3. Acceptable limits of operative temperature ranges for free-running, naturally conditioned spaces based on 3 categories. The acceptability bands are: Tcomf ±2, Tcomf ±3 and Tcomf ±4°C for categories I,II and III respectively. (Source: developed from BS EN 15251 (2007).

In this standard, the adaptive model is only applicable to buildings without cooling systems. But in contrast to ASHRAE-55, the acceptable ranges of indoor operative temperature are defined by the three building categories (i.e., I, II, III) used in EN 15251 (2007), based on the nature of the building rather than the quality of their indoor environment (Nicol et al., 2012), as seen in Table 2.3. These categories are assigned to overcome the tendency of ISO 7730 classes to favor high-energy buildings, as noted by Nicol et al. (2012). As for thermal comfort zones, as seen in Figure 2.3, EN 15251 defines acceptable limit ranges of operative temperature for each category, based on their deviation from comfort temperatures defined by the equation.

Table 2.3 Recommended categories and their associated acceptable temperature ranges for mechanically conditioned (PMV-PPD) and free-running buildings, based on ISO 7730 (2005)

Category	Explanation	Thermal state of the body as a whole [mechanically conditioned (PMV-PPD)]		Acceptable indoor temperature for free-running buildings	Operative temperature °C [classroom sedentary ~1.2 met]	
		PPD %	Predicted Mean Vote	Upper and Lower limit equations	Minimum for heating (winter season), ~1.0 clo	Maximum for cooling (summer season), ~0.5 clo
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	**< 6**	**-0.2 < PMV < + 0.2**	**Θ_i max =** $0.33\Theta_{rm} + 18.8 + 2$ **Θ_i min =** $0.33\Theta_{rm} + 18.8 - 2$	**21.0**	**25.0**
II	Normal level of expectation and should be used for new buildings and renovations	**< 10**	**-0.5 < PMV < + 0.5**	**Θ_i max =** $0.33\Theta_{rm} + 18.8 + 3$ **Θ_i min =** $0.33\Theta_{rm} + 18.8 - 3$	**20.0**	**26.0**
III	An acceptable, moderate level of expectation and may be used for existing buildings	**< 15**	**-0.7 < PMV < + 0.7**	**Θ_i max =** $0.33\Theta_{rm} + 18.8 + 4$ **Θ_i max =** $0.33\Theta_{rm} + 18.8 + 4$	**19.0**	**27.0**

Source EN 15251 (2007)

Θ_{rm} = Running mean outdoor temperature °C, Θ_i = Limit value of indoor operative temperature ºC.

Because the SCATS project was significantly smaller in sample size than ASHRAE RP-884 by de Dear and Brager, it relied on the Griffiths method to derive neutrality (comfort temperature), with inherent uncertainties as noted by de Dear et al., (2013). In the same study, de Dear et al., (2013) describe Griffiths constant as a "presumed rate of change of building occupants' thermal sensation with respect to indoor operative temperature, and it is used to extrapolate beyond the range of temperatures observed in the building to the point where neutrality might be expected to occur in the absence of any adaptation by the occupants" (p. 444). The extrapolation of this constant has been questioned and studied in various studies (de Dear et al., 2013; Shamila Haddad, Osmond, & King, 2017a; Shamila Haddad et al., 2019), including recent research by Nicol and Humphrey.

2.6.3. **ISO 7730:** Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort calculation of the PMV and PPD indices and local thermal comfort criteria.

The International Standards Organization (ISO) is an independent, non-governmental organization with a membership of 164, in which the ISO 7730 becomes a national standard. The ISO 7730 (2005) is based on the heat balance model developed by (Fanger, 1970), to predict the thermal sensation using the PMV/PPD indexes. Additionally, it sets criteria for local thermal discomfort, which can be caused by: 1) draft, by calculating a draft rate (DR); and 2) vertical air temperature differences or air stratification between ankles and head, and between warm or cold floors and ceilings. The latter are determined by a percentage (%) of dissatisfied (PD) as seen in Table 2.3.

The standard identifies three different categories or "classes" of buildings (i.e., A, B, C) based on percentages of acceptability (i.e., 94%, 90%, and 85%). Within these categories, it sets ranges for PMV and percentages for PPD, 6%, 10%, and 15% respectively, as seen in Table 2.3. Similar to the EN 15251 Standard, it suggests ranges of operative temperature for each category for winter and summer (ISO 7730, 2005), under certain assumptions for typical activity and clothing insulation levels. For example, as specified for classroom spaces (category B), it assumes an activity level of 1.2 Met (i.e., sedentary) and suggests ranges of operative temperature for winter with 1.0 clo of 19°C to 25°C, and summer with 0.5 clo of 22°C to 27°C, as seen in Table 2.3. Even though the standards recognize classroom spaces, the thermal comfort criteria are the same as for other building types, such as office spaces occupied by adults in sedentary or near sedentary activities. The latter is not too representative for school children's activity levels or ranges of temperatures, as suggested by other studies (Mors et al., 2011; Teli, Jentsch, & James, 2012). Additionally, it is assumed to apply to all age groups.

This standard does not include an adaptive model, as ASHRAE and EN 15251 do. However, it does provide measured values for typical adult office garments and ensembles for different clothing insulation. Due to international coverage, ISO 7730 has been significantly referenced by many countries, but at the same time it has been scrutinized for its validity for predicting thermal comfort in everyday life, however, is has not been revised since 2002 (Humphreys & Nicol, 2002b).

2.7. Approaches in IAQ assessment

Indoor Air Quality in school buildings is an important aspect of the learning process, and improving IAQ conditions should be given as much concern as new teaching methods or improving educational systems (Wargocki & Wyon, 2006). The study by Mendell et al. (2006) addressed that poor IAQ can affect learning outcomes by impairing concentration and memory during class time and indirectly by affecting health and well-being by exacerbating diseases such as asthma and allergies, which can affect students attendance and performance (Mendell et al., 2006 as cited in Mansour, 2014). However, as noted in the review study by Mendell & Heath (2005), teachers and school staff also can see their health and productivity being affected by poor IAQ. Additionally, not only can students' and teachers' academic performance be impacted, but also government funding can be decreased due to their absences, affecting the overall school budgets (Mansour, 2014).Therefore, it is essential to understand and review the current sets of international standards and guidelines that can contribute to good IAQ in school buildings.

Determining the best approach for removing indoor air pollutants has been debatable, but the most obvious is to "remove or reduce the source of pollutant or to increase ventilation rate in order to dilute or dispose of particles and to keep its concentration below a proven acceptable range" (Holladay, M. 2013, as cited in Passe & Battaglia, 2015). On the other hand, these acceptable ranges can vary significantly over time from standard to standard.

The following section will cover different international standards and guidelines that can apply to school environments by specifically looking at those available in the US and Worldwide.

2.8. International Standards and Guidelines for Indoor Air Quality

Providing good air quality inside buildings requires having sufficient ventilation rates that can remove pollutants, therefore reducing the impact on human health. Ventilation is a process that exchanges indoor polluted air with outdoor (presumably) fresh and clean air. While some studies have investigated levels of pollutants (i.e., pollutants related to human activities such as combustion, smoking, cooking, etc.) inside school environments, the vast majority have focused on CO_2 concentrations and ventilation rates (i.e., pollutants related to human occupancy). CO_2 indoor concentrations are produced by metabolic breathing of occupants and are considered a reliable indicator for estimating ventilation rates in a space. As seen in Figure 2.4, increased outdoor airflow rates dilute indoor CO_2 concentrations levels in naturally and mechanically ventilated classrooms, as seen in the results of a meta-analytic study by Chatzidiakou, Mumovic, Summerfield & Dockrell (2012; 2014). The findings of Chatzidiakou et al. (2014) show a higher number of studies are concentrated in the lower range of ventilation rates and high CO_2 concentrations levels, suggesting this is a typical pattern in school settings. However, CO_2 and ventilation rates are only indicators of occupancy and not traffic-related pollutants.

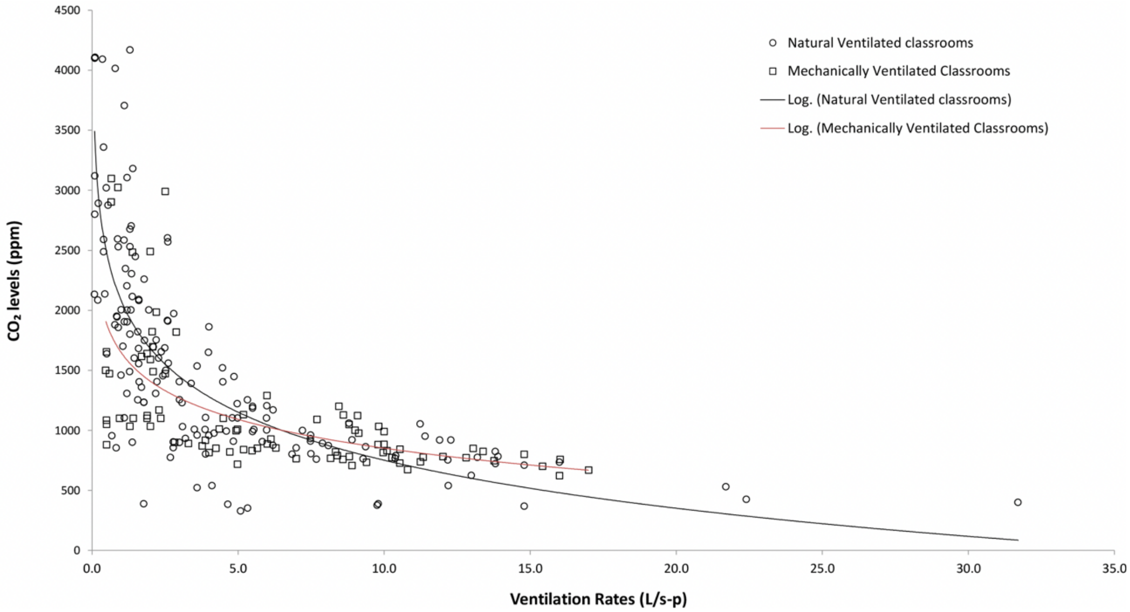


Figure 2.4 Correlation between indoor CO_2 concentration levels and ventilation rates in naturally and mechanically ventilated classrooms synthesized meta-analytic study by Chatzidiakou, et al. Source Chatzidiakou, Mumovic, Summerfield & Dockrell (2012; 2014).

Additionally, because of the negative impact indoor air pollutants can have on human health and well-being, particularly in the elderly and young children, it is of great concern to government agencies, regional and worldwide organizations. Therefore, these organizations, such as the World Health Organization (hereafter WHO), have stipulated a set of guidelines and standards with a general sense of consensus of limiting humans to the exposure of specific air contaminants based on scientific research (Ahmed Abdul–Wahab, En, Elkamel, Ahmadi, & Yetilmezsoy, 2015, p. 751). It is important to note that these guidelines and standards are oriented in two forms, those for workers (i.e., occupational) and those for other populations, such as children and the elderly (non-occupational) (Al-hemoud, 2017).

The WHO (2005, 2010) IAQ guidelines provide a scientific basis for legally enforceable standards applicable to non-occupational environments, such as households, schools, day-care centers, and vehicles. The WHO 2006 and 2010 guidelines focus on pollutants that are often found indoors, and they provide maximum acceptable thresholds for the exposure of indoor pollutants that pose health risks, as seen in Table 2.4.

Table 2.4 WHO guidelines of maximum acceptable levels of indoor pollutants

Pollutant	***Units***	***Short-term Exposure***	***Annual Average Exposure***
$PM_{2.5}$	µg/m^3	25 (24-h mean)	10
PM_{10}	µg/m^3	50 (24-h mean)	20
NO_2	µg/m^3	200 (1-h mean)	40
O_3	µg/m^3	100 (8-h mean)	
CO	mg/m^3	100 (15 minutes)	
		35 (1-h)	
		10 (8-h)	
		7 (24-h)	

Source: (WHO, 2005, 2010) developed from Chatzidiakou et al. (2014)

From the literature review study by Ahmed Abdul–Wahab et al. (2015), frequent air pollutants that contribute to poor IAQ and negatively impact human health are: carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), total volatile organic compounds (TVOCs), and particulate matter ($PM_{2.5}$ and PM_{10}). Additionally, thermal comfort parameters (i.e., air temperature, airspeed, and relative humidity) have also been further associated with IAQ and indoor environments (Abdul–Wahab et al., 2015).

2.8.1. ASHRAE 62.1: The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants, and that minimizes adverse health effects (ASHRAE 62.1, 2016).

2.8.2. WHO: Guidelines are intended for indoor settings like homes, schools, daycare centers, and vehicles occupied by the general population or susceptible population groups like children, the elderly, or asthmatics. "The aim of these guidelines is to provide a uniform basis for the protection of public health from adverse effects of indoor exposure to air pollution, and to eliminate or reduce to a minimum exposure those pollutants that are known or are likely to be hazardous" (WHO, 2010, p. 16).

2.8.3. National Ambient Air Quality Standards (NAAQS) /Environmental Protection Agency (EPA): The Clean Air Act, last amended in 1990, requires the EPA to set NAAQS for pollutants considered harmful to public health and the environment. The Clean Air Act identifies two types of national ambient air quality standards. Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. *Secondary standards* provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings (EPA, 2016).

2.8.4. Occupational Safety and Health Administration (OSHA/USA): under the US Department of Labor, this standard is intended for employers that must comply with all applicable OSHA standards (not intended for homes or schools, etc.).

Table 2.5 summarizes standards and guidelines for different air pollutants based on the review studies of (Ahmed Abdul–Wahab et al., 2015; Al-hemoud, 2017; Chatzidiakou et al., 2014, 2012).

Table 2.5 Summary of international air quality standards and guidelines for $PM_{2.5}$, PM_{10} and CO_2

Pollutant	***Country***	***Value***	***Organization***
CO	US	9 ppm as 8-h aveg. (Maximum or peak level)	ASHRAE
	US	35 ppm (40,000 µg/m^3) as 1-h aveg. 9 ppm (10,000 µg/m^3) as 8-h aveg.	NAAQS/EPA NAAQS/EPA
	Worldwide	90 ppm as 15-min aveg. 50 ppm as 30-min aveg. 25ppm as 1-h aveg. 10ppm as 8-h aveg.	WHO
CO_2	US	<700 ppm (1800 mg/m^3) above outdoor ambient (<800 ppm prefer)	ASHRAE
	US	800 ppm (allowable air concentration levels)	US/EPA
	US	5,000 ppm (9000 mg/m3) as 8-h working day, 5-d working week	OSHA
	Worldwide	1,000 ppm	WHO
$PM_{2.5}$	US	65 µg/m^3 as 24-h aveg. (exposure)	ASHRAE
	US	35 µg/m^3 as 24-h aveg. 15 µg/m^3 as 1-h aveg.	NAAQS/EPA
	US	5 µg/m^3 as 8-h aveg.	OSHA
	Worldwide	25 µg/m^3 as 24-h aveg. 10 µg/m^3 as 1–y aveg.	WHO
PM_{10}	US	150 µg/m^3 as 24-h aveg.	ASHRAE
	US	150 µg/m^3 as 24-h aveg. 50 µg/m^3 as 1–y aveg	NAAQS/EPA
	Worldwide	50 µg/m^3 as 24-h aveg 20 µg/m^3 as 1–y aveg	WHO

Source: adopted from Ahmed Abdul–Wahab et al., 2015; Al-hemoud, 2017; Chatzidiakou et al., 2014, 2012, US/EPA, NAAQS/EPA, WHO (2010), ASHRAE 62.1 (2016)

2.9. Chapter summary

This chapter provided background information about definitions of thermal comfort and indoor air quality, with their corresponding measurement parameters and different evaluation approaches commonly found in the literature. Additionally, it covered research on thermal comfort that has led to the development of different models for thermal comfort evaluation and current international standards derived from previous research. On the other hand, current IAQ international standards and guidelines are presented that can apply to school settings and that can help prevent or minimize pollutant exposure posing health risks. Overall, limitations are presented with regard to how current models, thermal comfort evaluations, and standards are limited in their applicability to school settings, particularly for young children.

CHAPTER III:

LITERATURE REVIEW

Research interest on thermal comfort and IAQ have noticeably increased greatly over the last two decades as seen in various literature review articles (de Dear et al., 2013; Halawa & Van Hoof, 2012; Rupp et al., 2015; Van Hoof, 2008). As evidenced by Rupp et al., (2015), a significant increase in thermal comfort field studies has occurred over the last ten years. Although the vast majority of these studies primarily focused on office settings with adult occupants in mechanically conditioned or naturally ventilated environments, studies of thermal comfort in schools have also been on the rise. The higher interest in the last decade on thermal comfort studies in schools goes together with the increasing concern regarding poor indoor environmental quality (IEQ hereafter) in classrooms. Of particular concern are high indoor temperatures, high relative humidity, and CO_2 concentration levels that have been reported inside classroom spaces, and their effects on children due to the significant amount of time they spend indoors during their developmental years.

In the study by Klepeis et al., (Klepeis et al., 2001) children younger than 12 years old on average spend approximately 80-90% of their time indoors (between school and home). More recent studies (Dessing. et al., 2013; Pagels, Raustorp, Guban, Fröberg, & Boldemann, 2016) show that children in the Netherlands aged 7 to 11 years old spend less than 40 minutes per day on the schoolyard.

Learning activities demand high levels of concentration, since students learn new topics and advance in their thinking skills; therefore, classroom design characteristics should provide a stimulating environment that promotes the learning process (De Giuli et al., 2012; Mishra & Ramgopal, 2013; Turunen et al., 2014). However, studies have shown that increased classroom temperatures (de Dear et al., 2013; Mendell & Heath, 2005; Wargocki & Wyon, 2007, 2013b), high CO_2 concentration levels, and low ventilation rates (Bakó-Biró, Clements-Croome, Kochhar, Awbi, & Williams, 2012; Haverinen-Shaughnessy, Shaughnessy, Cole, Toyinbo, & Moschandreas, 2015; Mendell, Eliseeva, Davies, Spears, Lobscheid, Fisk, & Apte, 2013) can have a negative impact on student performance and well-being. As noted by Mendell and Heath (2005), young children are more susceptible to environmental pollutants than adults.

The following literature review covers research on the impacts of IEQ on children's performance in school through field studies, together with new research on thermal comfort and indoor air quality in school buildings.

3.1. Thermal Comfort Studies in Schools

Thermal comfort studies on children have been conducted in several countries, in different climates and cultures. In a recent review article by Zomorodian, Tahsildoost, & Hafezi (2016a), field surveys of thermal comfort have been conducted on different educational levels. In this review, they classified students into three groups: 1) primary (students of 7-11 years of age), 2) secondary/high school (12-17 years of age), and 3) university levels (18-28 years of age). As pointed out in the study, they include the application of questionnaires while collecting measurements of indoor physical parameters (i.e., air temperature, relative humidity, air velocity, and global temperature) to validate thermal comfort models and to understand the perception of students under those conditions. As evidenced in this article and also in the general literature, thermal comfort studies have mostly been performed on higher educational levels (i.e., university), followed by secondary/high school. Studies in primary schools make up small numbers compared to the previous groups, and the studies have mainly been performed in Europe (Zomorodian, Tahsildoost, & Hafezi, 2016). The latter can be explained by the difficulty that has been associated with young children of this age group understanding thermal comfort (Baker, 2011).

In the same review article by Zomorodian, a comparison of neutral/comfort temperatures in different climates shows that the lowest and highest limits of comfort temperature are in temperate and tropical climates. Neutral temperatures in terms of operative temperature ranged from 16.7–29.2 °C. The lowest temperature was reported in winter temperate climate in Chile and the UK. The study suggests that students preferred temperatures by 1.5 to 4 °C lower than the model predictions (Zomorodian et al., 2016). In the same study, a narrower comfort bandwidth is inferred from children in primary school, as compared to the older categories. Studies have also indicated that thermal neutralities show considerable variation among similar climates (e.g., temperate) across winter, spring, summer, and fall for naturally ventilated classrooms (de Dear, Kim, Candido, & Deuble, 2015). In some locations, students that are exposed to broader weather variations show greater thermal adaptability than those in more uniform weather locations (Hussein & Rahman, 2009; Kwok, 1997).

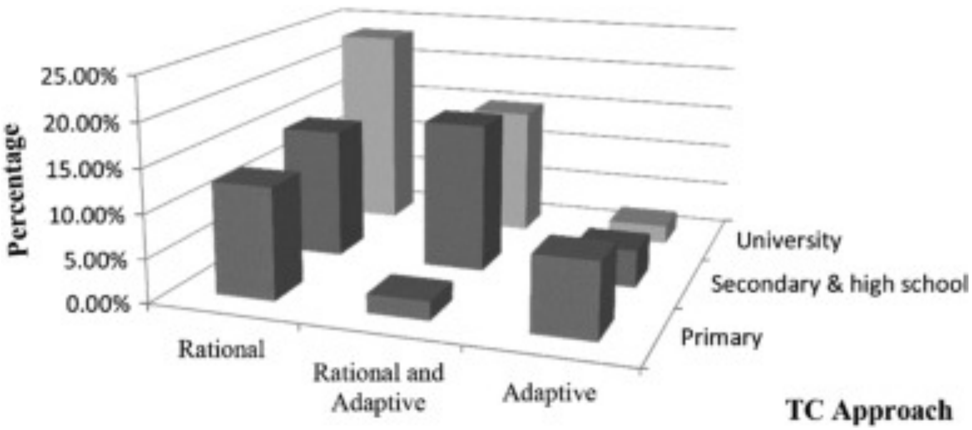


Figure 3.1 Comparative graph of the percentage of number of studies of different thermal comfort approaches in different educational stages. Source from Zomorodian et al., (2016)

Different studies have discussed the suitability and the reliability of the heat balance (steady-state/rational) and adaptive models in predicting thermal sensation and comfort of students in classroom environments. As noted in the review by Zomorodian et al., the adaptive model has been adopted in primary classrooms more than any of the other educational stages (i.e., secondary and university) to evaluate thermal comfort, as seen in Figure 3.1. However, the most common and widely applied approach in all educational levels has been the rational PMV–PPD model.

In the literature, thermal comfort field studies conducted in classrooms have found a mismatch between comfort predictions and requirements specified in adults' thermal comfort standards (Shamila Haddad et al., 2017a). Teli, Jentsch, & James (2012a; 2012b) developed a field study in the UK with children aged 7-11. From their findings, both PMV and PPD models were very limited in predicting thermal comfort for children, i.e., underestimating the actual thermal sensation of children, whereas in studies on adults in naturally ventilated buildings PMV predictions overestimates adults' thermal sensation votes (Shamila Haddad et al., 2017a, p. 458). The results of Teli, James, & Jentsch (2013;

2015) suggest that children are more sensitive to higher temperatures than adults, calculated comfort temperatures from survey responses are 4°C (steady-state/rational) and 2°C (adaptive) lower than comfort model predictions. The same was proven by Mors, Hensen, Loomans, & Boerstra (2011) and de Dear et al., (2015). From the study by de Dear et al., (2015) in Australia, the indoor operative comfort temperature was estimated to be 22.5°C. This value corresponds to the neutral and preferred temperature, which is cooler than expected for adults under the same thermal conditions (de Dear et al., 2015).

In a study by Haddad, Osmond, and King, (2016) in Iranian primary schools, the results suggested the comfort temperature predicted by ASHRAE's adaptive comfort model are higher than those derived from children's responses, i.e., 26.5 °C (Shamila Haddad et al., 2017a), thus implying that children require colder operative temperatures to achieve thermal comfort. Shamila Haddad et al., (2019) in a follow-up study, used a different method to calculate children's neutral temperature through the Griffiths method. The method estimates a comfort temperature or neutral temperature "of a particular person in a particular building in a particular month" as seen in equation 3.1. Where T_{op} is the mean operative temperature, TSV is the thermal sensation vote, and a standard regression coefficient (b) taken as the Griffiths constant (Haddad et al., 2019; Humphreys, Rijal, & Nicol, 2013).

$$T_{comf}=T_{op}-TSV/b \qquad \text{(Eq. 3.1)}$$

Shamila Haddad et al., (2019) results show 2°C higher than those based on regression analysis of TSV responses against the classroom operative temperature (2019, p. 185). From their findings, it is appropriate to use the Griffiths constant of G= 0.5 (Griffiths, 1991; Nicol & Humphreys, 2010; Nicol et al., 2012) for the sampled children, which is also in agreement with the study by Teli et al., (2015). But as suggested by Haddad et al., this requires proper validation studies in different climates. Based on the refinements done by Haddad et al. (2019), their findings shows that the preferred metric for children studies is the prevailing outdoor temperature, which is calculated as the exponentially weighted running mean outdoor temperature, with α in the range of 0.45 to 0.65 (Haddad et al., 2019; Humphreys et al., 2013). However, further studies with a larger sample size in different climates and cultures may help improve the values of G and α for children.

The study conducted by Hussein, Rahman, & Maria (2009) in two schools located in the hot/humid climate of Malaysia reported that 80% of the students found the thermal environment acceptable. The actual sensation vote (ASV) exceeded the comfort temperature ranges predicted by ASHRAE-55 (Ibrahim Hussein, Rahman, & Maria, 2009; Rupp et al., 2015). The neutral temperature was 28.4 °C for non-air-conditioned buildings obtained by regression analysis of TSV on operative temperature. This clearly shows that students in this region have a higher tolerance to heat, which is different to the results from the locations in the studies of Teli, Mors, Haddad, and de Dear et al., (2015; 2017a; 2011; & 2013), suggesting that thermal perceptions vary depending on climate zones, study setting and culture.

Studies have also shown, thermal neutralities show considerable variations among similar climates (e.g., temperate) across winter, spring, summer, and fall for naturally ventilated classrooms (de Dear et al., 2015). In some locations, students that are exposed to broader weather variations show greater thermal adaptability than those in more uniform weather locations. However, more research is required in this area, investigating different climates and cultural backgrounds, in order to help understand children’s perceptions and adaptability.

Children’s different physical and physiological characteristics can explain the differences between the calculated thermal indices and children's thermal perception and preferences in comparison to adults. As noted in the literature, physical and physiological differences between children and adults include surface-area-to-mass ratio, blood volume per body surface area, sweating rate, metabolism, body temperature, and circulation (Falk, 1998). These factors can affect the thermoregulation and the mechanisms the human body employs to reach a heat balance. Children and babies have a limited ability to thermoregulate. Children employ different thermoregulatory processes than adults do (Kovats & Hajat, 2008). For example, they have a higher metabolic rate while sitting (Teli, Jentsch, & James, 2012), a faster rate of heat loss (McCullough Eckels, & Harms, 2009) and a higher sensitivity to core temperature change (Anderson & Mekjavic, 1996), which occur within a narrower range of conditions (Lundgren, Kuklane, Gao, & Holmér, 2013; Parsons, 2014).

Concerns have also arisen about the use of an adult metabolic rate to calculate the PMV model for children, as investigated (by Teli et al., 2012). In Teli’s study (2012), different approaches to calculate metabolic rates and clothing insulation values for different school uniform combinations were addressed. The best approach determined by this study was “body surface area correction of the input activity metabolic rate and resting metabolic rate, both in the ‘met’ calculation and inside PMV equation” (2012, p. 170). The calculated input activity (70 W/m^2) and the resting metabolic rate (58.15 W/m^2) were corrected for the reduced surface area of a child (i.e., 1.14 m^2). Thus the metabolic rate of sedentary school activity of 58 W/m^2 and resting metabolic rate–RMR of 48.8 W/m^2 (1.60 W/kg) 'met' value for sedentary activity for PMV calculations is 1.2 Met (2012, p. 170).

Another possible explanation is that children do not tend to behave adaptively (i.e., change clothing, or open a window) when they feel uncomfortable in indoor conditions, while adults do. Different characteristics of classroom environments compared with adults' work/office spaces can influence children's perceptions of thermal comfort and level of satisfaction. For example, children conduct more physical activities such as playing in the schoolyard three to four times a day when they are not sitting in a classroom, a much different situation than in an office space, where people tend to stay in a sedentary position all day. Therefore, the daily routine of a young student is much more active than that of a typical office employee, which can influence their thermal perception of comfort (Teli et al., 2013).

As more studies use the adaptive model for school fieldwork, questions arise as to its suitability. Since it only takes into account the recent outdoor temperature history for predicting the comfort temperature range, it may not accurately predict the thermal sensation of occupants (Zomorodian et al., 2016a). The concept of adaptive behavior assumes that there is an active effort by the individual to achieve thermal comfort (i.e., to open a window). However, the concept is questioned in classroom environments, where adaptability can be limited. Many studies have addressed the fact that the thermal environment of a classroom relies more on the preferences of the teacher than the students

(Kim & de Dear, 2018b; Montazami et al., 2017a), which limits the opportunities for adaptive behaviors of student in schools, particularly at the primary level. In the study by Montazami et al., results suggest that the percentage of children satisfied with the indoor temperature is significantly higher in the classroom where students ask teachers to open windows or doors rather than make personal changes to their clothing (Montazami et al., 2017a, p. 69). However, Kim & de Dear (2018b), showed that primary school children are more responsive to outdoor conditions, by adjusting their clothing when the temperature became warmer, in comparison to secondary school students. High school students were more forthcoming in expressing their desire to change classroom environments to teachers by turning on the AC, opening windows or adjusting curtains or blinds before making personal changes (Kim & de Dear, 2018b).

Additionally, in many countries schools have dress code policies that require students to wear uniforms, which limit their opportunity to modify clothing during the day based on outdoor weather conditions. Adaptability has also been questioned when personal adaptation is limited, due to religion and particular cultural customs, as various studies have shown (de Dear et al., 2015; Haddad et al., 2019; Montazami, Gaterell, Nicol, Lumley, & Thoua, 2017c; Teli et al., 2013). Furthermore, studies have addressed the need to recalculate clothing insulation values to better represent children's school uniforms based on local fabrics instead of office garments as assumed in international standards (i.e., ASHARE-55 2017, and ISO 7730-2005). From the literature, studies have estimated clothing insulation based on field observation, through different combinations of school uniform garments worn by students during the study period (de Dear et al., 2015; Haddad et al., 2017).

Adaptation can also be limited regarding the control provided to the occupants to change the indoor conditions; for example, access to operable windows, shading devices, and thermostats (de Dear et al., 2013; R De Dear et al., 2015; Shamila Haddad et al., 2017; Mors ter et al., 2011; Teli, Jentsch, James, et al., 2012). Studies in office buildings have shown the importance of well-integrated design where the mechanical and natural systems can work well together (Brager & Baker, 2009), and occupants seem more satisfied with their indoor environments when personal control is provided (Bluyssen et al., 2015; Schweiker et al., 2013). Children, however, are passive agents of their environmental conditions, which are selected by others (i.e., teachers) rather than themselves for their comfort (De Giuli et al., 2012; Kim & de Dear, 2018b). The individual's control should be further studied for different educational levels, since awareness of thermal perception and adaptation in children might be less and different in young children than in teenagers, from primary to secondary school.

Also, thermal background, as related to various socioeconomic groups, has been suggested to influence thermal perceptions by children (Montazami, Gaterell, Nicol, Lumley, & Thoua, 2017c; Trebilcock, Piderit, Soto, & Figueroa, 2016; Trebilcock, Soto-Muñoz, Yañez, & Figueroa-San Martin, 2017b). In the study by Montazami et al., (2017c) the perception of thermal comfort is not purely dependent on indoor classroom temperatures, but it can be affected by the children's socioeconomic background and what they experience at home. The study "results suggested that socio economic background has a significant impact on a child's behavior", through Chi Square test, ($X^2 = 13.83$, df = 3, $P = 0.003 < 0.05$) (Montazami et al., 2017c, p. 431). Montazami et al., addressed that privileged children are more likely to make independent decisions and adopt personal behaviors than less privileged children, who might tolerate uncomfortable conditions or depend on teachers to take actions. The findings (of Trebilcock et al., 2017b) support this idea. Their study suggests that children that come from deprived environments (i.e., low income) adapt to lower temperatures better than those who come from less deprived ones (Trebilcock et al., 2017a, p. 468). Only these two studies have addressed how socioeconomic background can influence thermal perceptions in children.

Future studies should investigate the impact of socioeconomic background on children's perceptions of comfort further as well as how adaptive standards should respond to these differences. The latter can help us to understand or explain the differences in neutral thermal perceptions between students of the same educational stage, as identified by Zomorodian et al. (2016).

Only a few authors have implemented new design methodologies to address issues associated with children's conceptual understanding of thermal comfort questionnaires that were initially designed for adults (S. Haddad, King, Osmond, & Heidari, 2012; Teli, Jentsch, James, et al., 2012). Although methods for improving data quality in surveying adults is well addressed (Leeuw, 2001), there is little information regarding how best to survey children. Haddad et al. (2012) looked at implementing design techniques to develop a useful questionnaire for evaluating children's perception of thermal comfort. They used simplicity and clarity on the questions, which translated into children quickly understanding what was asked. The use of pictures and illustrations was implemented, which conveyed facial expressions through cartoons to illustrate the ASHRAE seven-point scale as an appropriate method to keep children engaged and motivated during the questionnaire (S. Haddad et al., 2012). Similar design strategies have been implemented in the study by Teli, Jentsch, James, et al. (2012), in which a minor modification to the ASHRAE seven-point scale was amended based on teachers' feedback into: "a bit cool," "a bit warm" and "Ok." Additionally, a color scale, icons, and cartoon images were displayed along with the questionnaire for easier understanding. Other authors have implemented these methods in their studies which have proven to be successful for children's understanding (Trebilcock et al., 2017a).

Finally, Korsavi and Montazami (2019), propose a valid and reliable method to study the adaptive behaviors of primary schools as a response to classroom's IEQ. The study includes a design questionnaire based on children's cognitive and linguistic abilities, together with a methodology to validate the questionnaire design and responses through a validating process. The authors propose an observation form to be completed alongside the self-reported questionnaire to record adaptive environmental behaviors. This is the first article that proposes a design methodology for field studies with children, specifically for primary schools. The results and suggestions from the study can shed light on how to improve surveying methods on children and to obtain validated data that can help researchers understand children's perceptions of comfort, and eventually help designers provide the best conditions for their classroom environments to enhance satisfaction, performance, and health.

3.2. Indoor Air Quality Studies in Schools

IAQ studies are concerned with the architectural design of natural ventilation systems or operable windows, heating, ventilation, and air-conditioning (HVAC) systems, together with the identification of sources of pollutants present indoors or that are coming from outdoor environments (Fabbri, 2015).

As evidenced in the literature, children are more vulnerable to airborne pollutants than adults because their developing lungs breathe more than twice the air compared to their body size (Mendell & Heath, 2005). Children also are less aware of communicating reactions to high-level pollutants than adults. Therefore, children can be at a higher risk than adults from poor IAQ. Rising respiratory diseases have led to increasing research on IAQ in school settings (Pierpaoli & Ruello, 2018), particularly after reports from the World Health Organization (WHO hereafter), concluded that asthma is the most chronic disease among children (Chatzidiakou et al., 2012). As shown in the Pierpaoli & Ruello (2018) bibliometric study, a high increase of publications related to IAQ occurred from 2010 to 2017, responding to the WHO publication guidelines for indoor air quality (WHO, 2010). However, even though WHO guidelines provide a basis for international standards for IAQ, the reliance on proxies for IAQ assessment and finding cause and effect have proven to show difficulties in identifying which specific pollutant can affect health. The association of school environmental exposures to specific health symptoms is challenging, as noted by the authors, since many confounding variables can contribute to such symptoms, such as conditions at home or outdoor exposure. Therefore, it is difficult to separate the contributions from school-based and non-school based exposures. Additionally, as seen in the literature, there are multiple assessment methods that pose challenges to the evaluation of spatial and temporal variations in school settings. The following section includes studies on IAQ in school buildings, existing conditions compared to international standards, and the implications for health and performance.

Seppänen & Fisk (2005) show that perceived air quality could affect the predicted acceptability of air quality (Park, 2015). In indoor environments, common types of air pollutants are carbon monoxide (CO), carbon dioxide (CO_2), Ozone (O_3), volatile organic compounds (VOCs) and particulates ($PM_{2.5}$ and PM_{10}) (Bernstein et al., 2008; Park, 2015). Detecting high concentrations of CO and CO_2 is hard because they are colorless and odorless (OSHA, 2002). One of the critical indicators of a building's IAQ is CO_2, which is associated with sick building syndrome (hereafter SBS) and ineffectiveness of ventilation rates (Gupta, Khare, & Goyal, 2007).

Chatzidiakou et al. (2012), investigated CO_2 concentrations through a meta-analysis of 14 published papers from 312 classrooms in 80 schools. From their findings, 30% of the investigated classrooms exceeded 1500 ppm. High CO_2 concentration has also been reported in other meta-analyses (Daisey, Angell, & Apte, 2003a; Haverinen-Shaughnessy et al., 2015; Mendell & Heath, 2005; Pawel Wargocki & Wyon, 2013b). Low ventilation rates, particularly in naturally ventilated classrooms, have been linked to adverse health effects on children as well as teachers. The transmission of respiratory infectious diseases is dependent on a fresh air supply and CO_2 concentration because airborne infections can only be transmitted by inhaling air that has been previously exhaled.

The study of Norbäck & Nordström (2008) shows a significant positive relationship between asthma symptoms and CO_2 concentrations for a threshold higher than 1000 ppm CO_2. The latter corroborates the findings of Smedje & Norbäck (2000), in which decreasing mean indoor CO_2 from 1050 to 780 ppm, after installing a new ventilation system that increases the air-exchange rate, helping to remove several airborne pollutants, resulted in a significant reduction of asthmatic symptoms in children from 11.1 to 3.4%. It is essential to guarantee good IAQ in school environments because children are more susceptible to indoor pollutants that can exacerbate diseases such as asthma or allergies since their tissues and organs are still developing.

Numerous studies have found high daily mean average concentration of particles such as PM_{10} or $PM_{2.5}$, exceeding recommended WHO guidelines in schools. In school environments, the primary sources of particles include human activities, plants, and building materials. Additionally, particles can also come from ventilation or infiltration from the outdoors, from vehicle exhaust in urban areas, or from wood-burning heating systems that predominantly exist in developing countries like Chile. In recent studies, mean indoor $PM_{2.5}$ and PM_{10} concentrations were found to be higher than average outdoor concentrations recommended by United States Environmental Protection Agency (USA EPA 2006) and WHO (Amato et al., 2014; Mohammadyan et al., 2017).

The study by Amato et al. found two activities common to children as sources responsible for indoor $PM_{2.5}$ concentration in primary classrooms in Barcelona, and seven other sources from outdoors. From indoor sources, 47% of $PM_{2.5}$ measured in the classroom was generated from the continuous suspension of soil and mixed sources comprised of organic (i.e., skin flakes, clothes fibers, possible condensation of VOCs) and calcium-rich particles (i.e., from chalk and building deterioration) (Amato et al., 2014). Emissions from seven outdoor sources easily penetrated inside classroom spaces and were responsible for 53% $PM_{2.5}$ of indoor concentrations. As noted by the authors, high exposure to PM $_{2.5}$ is due to poor orientation of classroom windows such as facing streets or main roads directly, poor building insulation (leaky envelopes), and unpaved playgrounds (Amato et al., 2014).

In Mohammadyan et al., 2017, a study in Northern Iran in six schools also found a mean indoor $PM_{2.5}$ (of 47µg m^3) and PM_{10} (of 397µg m^3) concentrations slightly higher than the EPA's 24–hour standards (US EPA 2006). However, in the study by Rovelli et al. (2014) , who measured $PM_{2.5}$ and PM_{10} in seven schools in Milan, Italy, indoor mean $PM_{2.5}$ concentrations were lower than average outdoor PM $_{2.5}$ (Rovelli et al., 2014). Limited empirical evidence exists on the concentration of ultrafine particles in the classroom and the potential effect it can have on children. Studies highlight the need of further investigations in this area to understand sources, chemical composition, and concentration levels of indoor PM, and short and long term exposures in schools in comparison to outdoor levels, particularly in different climates and urban contexts.

3.3. IEQ effects on students' heath and performance

3.3.1. Temperature on performance and well-being

Thermal conditions can affect the performance of office work or school work through at least six different mechanisms as described by Pawel Wargocki & Wyon (2016): 1) Thermal discomfort distracts attention; 2) warm temperatures lower arousal (the state of activation of an individual), exacerbate and increase the prevalence of sick building syndrome (SBS), thus a negative effect on cognition; 3) cold conditions can affect extremities of the body like our fingers which can lower our manual dexterity; 4) "rapid temperature swings can have the same effects on office work as slightly raised room temperatures" (Pawel Wargocki & Wyon, 2016); 5) vertical thermal gradients reduce perceived air quality at the head height, which can result in occupants' complaints and discomfort; 6) raised temperatures can result in higher levels of CO_2 in the blood that can cause headaches.

As seen in the literature review of thermal comfort studies on children, lower indoor operative temperatures are more comfortable for children than for adults. Lower temperatures can also improve children's health and their cognitive performance (Haverinen-Shaughnessy et al., 2015; Mendell & Heath, 2005). Reducing the temperature by 1°C within the range of 20 to 25°C can improve performance on standardized tests by 2–4% (Pawel Wargocki & Wyon, 2007). Air temperature has been commonly used as an indicator of thermal comfort and performance. Research has focused on finding a relationship between performance and air temperature in school settings (Cui et al., 2013a; Pawel Wargocki & Wyon, 2007, 2013b; Zhang & de Dear, 2017). However, controversy and differences of opinion exist on how to determine productivity or human mental performance.

One side of the spectrum looks at a single optimal temperature, while others look at a broad range of temperatures (de Dear et al., 2013; Wargocki & Wyon, 2007, 2013; Zhang & de Dear, 2017). It has been argued that free-running school buildings promote energy savings by reducing fan energy use and allowing a broader range of temperatures. At the same time, such strategies can be counterproductive because they can reduce school performance by allowing higher temperatures. Many of the studies that have looked at the relationship between air temperature and performance have predominantly been conducted in steady-state thermal conditions, (i.e., climate chambers) simulating office settings. However, several authors have questioned whether such conditions should be re-evaluated in real environments. Limited field studies exist in the literature in school settings under natural conditions, even less in naturally ventilated classrooms.

Performance has been reported to peak at a PMV value of -0.21 at a temperature of 20°C with a relatively heavy clo value (i.e., 1.16 clo), as reported in Kosonen & Tan (2004). Similarly, in the study by Lan, Wargocki, & Lian, (2011), optimum performance was about a TSV value of -0.25, in a controlled environment where a wide range of tasks including arithmetical calculation, typing, logical reasoning, and memory were carried out. Cui, Cao, Park, Ouyang, & Zhu, (2013) evaluated the effects of air temperature on thermal comfort, motivation and performance, and their relationship. In a climate chamber setting, five different temperature settings were evaluated (i.e., 22°C, 24°C, 26°C, 29°C, 32°C), finding an optimum temperature range between 22°C and 26°C. A warmer environment, as noted by the authors, has a negative effect on motivation and performance (Cui, Cao, Park, Ouyang, & Zhu, 2013).

A study by Zhang and de Dear (2017) on university students confirms that simpler cognitive tasks are less susceptible to temperature effects than more complex tasks. At a cooling set point of 22°C, subjects' cognitive performance was relatively stable, but at 24°C, subjects' reasoning and planning performance declined at a higher heat intensity and more prolonged heat exposure (Zhang & de Dear, 2017).

Although there has been increasing interest since Mendell's et al., (2005) publication looked at the relationship between thermal comfort and productivity, it requires more attention and further research in real conditions in naturally ventilated buildings to look at how temperature affects children's performance. One of the critical issues that has not been addressed is the use of multiple methods to estimate productivity and how it is defined, therefore hindering any comparison between studies. Future studies should look at methods to estimate performance and thermal comfort in school settings through the standardization of methods, thus resulting in a better understanding of these relationships, and how to provide better learning environments.

3.3.2. IAQ effects on performance and well-being

Occupants can be affected by the change in air quality, which can be manifested by mechanisms such as sneezing, eye irritation, or yawning when air quality is uncomfortable (Wolkoff, Wilkins, Clausen, & Nielsen, 2006; Park, 2015). Factors of good IAQ have been associated with appropriate ventilation, which has been a concern particularly with the implementation of the standard ASHRAE-62 in 1973, now ASHRAE 62.1 and 62.2 for Ventilation and Indoor Air Quality. Good IAQ has been associated with ventilation rates, just as one indicator, until the 1990s when it was considered a source of control, due to the effects related to SBS. Thus, it was acknowledged that occupants are not the only source of polluters in indoor environments (Bluyssen et al., 2016; Bluyssen, 2012). There are six mechanisms by which cognitive performance is affected by air quality: 1) distraction and attention, 2) motivation, 3) arousal and neurobehavioral symptom, 4) acute health symptoms, 5) sleep quality, and 6) absenteeism. Indoor air pollutants that can be present in work or school environments can trigger inflammatory or allergic responses and stimulate nerve endings in the nose and eyes, causing irritation and disrupting endocrine function (Pawel Wargocki & Wyon, 2016).

The relationship between ventilation rate and how it could influence performance was addressed in office environments by Fisk (2002), and Seppänen et al., (Seppänen, O., Fisk, 1999; Seppänen et al., 2005). The former “estimated the relationship between ventilation rate of naturally ventilated office spaces and absence from work” while the latter focused on “how ventilation rate affects work performance.” Ventilation rate, as it was approached in Seppänen et al., can indirectly influence performance through short-term sick leaves due to “infectious diseases, the prevalence of sick building syndrome (SBS) symptoms, or dissatisfaction with air quality” (Seppänen et al., 2005). In this study, the authors were able to demonstrate that “performance increases statistically significantly with the increase of ventilation rate up to 15 l/s-person with a 95% confidence interval” (Seppänen et al., 2005).

In school settings, various studies have explored the association of IAQ with student performance by analyzing the association of test scores or reduced attendance with the effects of an increased ventilation rate. In many of these studies, indoor CO_2 concentration have been used as surrogates for the ventilation rate (Mendell, Eliseeva, Davies, & Lobscheid, 2016; Petersen, Jensen, Pedersen, & Rasmussen, 2016; Salthammer et al., 2016; Shaughnessy, Haverinen-Shaughnessy, Nevalainen, & Moschandreas, 2006). Studies have found that "increased classroom ventilation rate indicated by the reduced CO_2 concentration increased the number of correct answers and decreased the number of errors in four different tests" (Petersen et al., 2016). Results from the studies are in some cases only modestly statistically significant, due to the small sample size. Also, the positive effect of ventilation on performance can only be determined over a short timescale, since it is unknown whether the level of performance is maintained over time.

Shendell et al. (2004) explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO_2). The results indicate that "1000 ppm increases in the difference between indoor and outdoor CO_2 concentrations were associated with 10-20% relative increases in student absence" (Shendell et al., 2004), which is suggested to be an indirect measure of student performance. A review study of ventilation rates in a classroom by Fisk, 2017, found compelling evidence that increasing ventilation rates increases students' performance by as much as 15%. Fisk found a consistent relation between high CO_2 concentrations in naturally ventilated classrooms, arguing that schools cannot "consistently rely on opening windows sufficiently to provide the recommended minimum ventilation rates" (Fisk, 2017, p. 11). Following this idea, Wargocki and Da Silva investigated the use of visual CO_2 feedback to reduce CO_2 levels in naturally and mechanically ventilated classrooms. From their findings, visual CO_2 feedback does improve the air of the classroom environments, but simultaneously increases the energy use for heating in temperate climates. At the same time, no significant relationship was seen between the perception of pupils with high CO_2 concentrations (Wargocki & Da Silva, 2015). Further studies should focus on the effects of ventilation over long periods of time and children's perceptions on high concentration of CO_2.

3.4. Thermal Comfort and IAQ field studies in primary schools in Chile

Research addressing environmental conditions in classrooms in Chile has been developed over the last six years in different climate zone conditions (i.e., North, Central, and South) and contextual settings. All the studies present in the literature are fieldwork assessments primarily focusing on thermal comfort perceptions of children and measurements of physical conditions of classroom environments. The majority of the case studies have been conducted in public schools during cold and warm seasons.

One of the first field studies in Chile was done by Armijo Whitman (2011) in 2009, who provided initial evidence regarding post-occupancy of physical conditions of school buildings that were built under the 1997 educational reform. This reform aimed to provide new school buildings as well as retrofit upgrades to existing schools to allocate students for fulltime mandatory enrollment. Before this reform, many public and subsidized schools offered half time enrollment. The indoor physical conditions (i.e., temperature, surface temperature, background noise levels, daylight, and indoor CO_2 concentrations) were measured and collected during the summer month of December in eight different schools in five different climate zones ranging from the northern to the southern parts of the country. The results indicated that poor conditions of noise pollution, daylighting, thermal comfort, and IAQ exist in the majority of the classrooms. In particular, high CO_2 concentrations were present, ranging from 900 to 1350 ppm on average, with a peak average of 2600 ppm in one school in the southern location. Authors noted that classrooms had low ventilation rates since windows were mostly closed due to outdoor noise levels and cold temperatures, thus contributing to high CO_2 concentrations.

Although this study provided the first glimpse of classroom conditions in Chile, it did not provide students' perceptions of their environments. The methods described by the authors had limited information about the procedures utilized, which compromises the analysis and interpretation of the results, as well as the replication of the study. Additionally, a small sample size of eight schools and field measurements was performed at the end of the school year, i.e., beginning of summer (mid-December), when students do not fully occupy the classroom due to summer holidays.

In a small study, Trebilcock et al. (2012) analyzed and compared two rural schools located in Curarrehue, in the southern mountain range of the Andes in Chile. This location has a high concentration of native indigenous people (i.e., Mapuches), which brings cultural sensitivity to the study. The study used ASHRAE 55 thermal comfort model to calculate PMV, to evaluate the thermal performance of the two different boarding schools designs. School 1: Rucamanke of Reigolil, was designed under the principals of "Mapuche Indigenous Architectural Design Guidelines," includes ancestral traditions of bioclimatic concepts and environmental principals of natives from Southern Chile. School 2: Francisco Valdes Subercaseaux (FVS) was designed under the principles of energy modern efficiency (Trebilcock, Bobadilla, et al., 2012). Physical measurements of air temperature, relative humidity, CO_2 concentrations, illuminance levels, background noise, and reverberation time were measured for two weeks during the winter and summer seasons. They found high concentrations of indoor CO_2, above 1000 ppm (16% in winter and 49% in summer) due to insufficient ventilation rates because of the airtightness of the school envelope. From the surveys, 79% of the occupants voted to feel comfortable with their thermal environment. Moreover, indoor temperature measurements ranged between 7°C and 17°C, which are very low compared to the range operative temperature for the heat balance or steady-state model in ASHRAE 55 of thermal comfort (i.e., 18°C to 24°C) (Trebilcock, Bobadilla, et al., 2012).

In another study, Trebilcock et al. (2017a) measured physical parameters while surveying children's thermal perceptions of their classroom conditions in primary schools in the city of Santiago, Chile. The study includes a sample of 12 primary school buildings, of 9 –10-year-old children. The study was performed during the winter months (July-August) and spring (November-December) in free-running public schools of low socioeconomic background. The results show that comfort temperatures from their field work are considerably lower than that calculated from the adaptive comfort formula, both for winter (14.7°C -15.6°C) and spring (22.5°C – 23.1°C). Thermal sensation vote for primary school students was also significantly lower (3°C to 4°C) from that predicted by ASHRAE's adaptive comfort model. The authors suggested that this might be explained by the higher metabolic rate of children. They also concluded that a high correlation exists between socioeconomic vulnerability and comfort temperature in winter, thereby suggesting that children who come from deprived environments tend to adapt to lower temperatures better than those who come from less deprived ones (Trebilcock et al., 2017a). However, their correlations only show a median strength association of r= 0.38 to r= 0.48 values, with negative associations between higher index of vulnerability and lower comfort temperatures in winter. The authors did not provide any information if this was statistically significant or not.

Additionally, questions arise as to how Trebilcock et al. defined the different socioeconomic groups, since it seems that they only focused on the "most vulnerable" and "vulnerable" socioeconomic groups (i.e., only low income), and the study did not include other groups such as private schools. Finally, a wide variation of indoor temperature (8°C – 20°C in winter and 16°C –32°C in spring) across classrooms was registered. The latter confirms the results from previous studies by Trebilcock et al. (Trebilcock, Bobadilla, et al., 2012; Trebilcock et al., 2016; Trebilcock, Soto, & Figueroa, 2012), and Armijo, Whitman, (2011), in which indoor temperatures in winter months are very low, and in spring very high, particularly for locations in warmer climate zones like Santiago, where overheating conditions can happen during spring months. It is concluded that children in primary schools are exposed to a wide range of indoor temperatures with high daily and seasonal variations, Trebilcock et al. (2017a).

Trebilcock et al. (2013, 2016), and Soto et al. (2015), also evaluate thermal performance and passive design strategies for 12 to 15 primary school classrooms in three different climate zones (i.e., Iquique “north,” Santiago “central,” and Puerto Montt “south”). In all three studies, physical environmental parameters were measured during three to four days in winter (July-August) and spring (November-December). The results again show high and low indoor temperatures during spring and winter, and a wide variation across the day for the vast majority of the classrooms analyzed. Trebilcock et al., (2016) also provided recommendations for passive-design strategies for each climate zone, based on a large number of combinations (parametric analysis) such as orientation, glazing area/floor area percentage, type of glazing, infiltration rate (ach), and thermal envelope.

Soto et al. (2015), including the data set from Trebilcock et al. (2013, 2016) also evaluated measurements of thermal comfort with the addition of indoor CO_2 concentrations for 15 public schools, across three different climate zones (i.e., northern, central, and southern parts of the country). Fieldwork demonstrates that the quality of the indoor environment in schools is outside recommended ranges of international standards (i.e., steady-state model of ASHRAE-55). As noted by the authors, classroom environments do not provide satisfactory conditions for the welfare and academic performance of students, and it is necessary to establish strategies that take into account an economic evaluation for heating and cooling systems when these are not present in classrooms (Soto et al. 2015) to improve indoor conditions. This study also identifies possible correlations between students' attendance and comfort indices such as PMV and PPD, as well as, children's attendance and temperature. However, since the data had a large dispersion, the authors were not able to directly link either classroom temperature and attendance or comfort indices with attendances, and the variance of their results remains uncertain. The authors additionally performed an analysis to relate average classroom temperatures with student attendance, but results do not provide a conclusive outcome and whether a significant correlation between the above variables exists.

Higher concentrations of CO_2 were measured, with concentrations exceeding 1,500ppm, while attendance surpassed 84%. The high number of students per classroom (i.e., ~35 students in 40 m^2) was related to high concentrations of CO_2 during winter, resulting in poor air quality. However, Soto et al. (2015)did not provide evidence to support that a relation between high CO_2 levels and students' attendance was statistically significant.

Their results underline a high density per classroom and minimal use of operable windows in winter for ventilation due to cold outdoor temperatures or noise levels.

3.5. Chapter Summary

This chapter presented a review of recent literature on thermal comfort and indoor air quality studies. With a primary focus on studies in school settings, results from the review shows that current international standards and criteria for the evaluation of thermal comfort, e.g., ASHRAE-55 (2017), ISO 7730 (2005), EN 15251 (2007), do not seem to be applicable for children, as they don't accurately predict their thermal sensation. It has been found in many field studies that PMV-PPD and adaptive models underestimate the actual thermal sensation of children, whereas in studies on adults in naturally ventilated buildings, PMV predictions overestimate adults' thermal sensation votes (Shamila Haddad et al., 2019; Kwok, 1997; Mors ter et al., 2011; Teli et al., 2013, 2015). Current standards are inappropriate for children in predicting their thermal sensation, as well as, assessing the thermal comfort in naturally ventilated classrooms, particularly in free-running buildings (Zomorodian et al., 2016a). This reinforces the need for more research and required changes in standards that address how to provide better indoor environments for this age group. Chapter 2 and 3 provide a theoretical framework on this research area and set the basis for how new research can respond to the different questions that emerge from investigating children's perceptions in primary school classrooms.

The literature points to the importance of providing comfortable indoor environments in school buildings, which can have a significant effect on children's performance as well as health and well-being, especially considering the time spent indoors during the developmental years of their life. It has been shown that higher temperatures can affect performance as well as thermal comfort, and research suggests that optimal indoor temperature ranges should be within 20ºC to 22ºC. However, performance evaluations have been conducted mainly in steady-state environments, and limited research exists on naturally ventilated conditions with primary school children. Additionally, even fewer studies have looked at thermal comfort and indoor air quality in a comprehensive manner, and how it can affect children's as well as teacher's perceptions of their classroom environments. Research has shown a strong correlation between low ventilation rates and high concentrations of air pollutants (i.e., CO_2, $PM_{2.5}$, and PM_{10}), which can adversely affect comfort and performance. Further research should address these relationships and how IAQ can influence thermal perceptions.

Differences in perception and thermal preferences between students and adults in office settings could be explained by the limited opportunities that children have in terms of changing classroom conditions and clothing adaptation in schools, as noted by many researchers (de Dear et al., 2013; R De Dear et al., 2015; Mors ter et al., 2011; Teli, Jentsch, James, et al., 2012; Trebilcock, Soto-Muñoz, et al., 2016). Because teachers are in control of classroom conditions, the adjustment of those conditions responds to teachers' preferences and perceptions, and not necessarily to those of their students. Only a handful of studies (e.g., Kwok, 1997) have evaluated simultaneously children's and teachers' thermal perception of their classroom conditions. Thus, our understanding of what conditions are best for teacher and students in the learning process is still rather limited. An substantial improvement in this matter requires the performance of more field studies that can provide more data on people's perception and preferences in different contexts.

Limited adaptation can also result in some countries, like Chile, that have strict dress code policies in which children are required to wear their school uniform throughout all grade levels (i.e., up to 12th grade level). Many schools do not allow students to remove layers or to add clothing that is not part of their uniforms, therefore affecting their thermal perceptions. Clothing insulation values in current standards are only based on adults' office garments, which highlights the need for more comprehensive data sets that include children's adaptation capability with respect to their clothing characteristics.

Reviews on primary schools suggest that children from this educational level have a narrower range of comfort temperatures compared to higher levels (e.g., secondary and university), based on results from field studies. However, only a limited number of studies have been conducted at the primary school level, particularly in cold outdoor temperatures, as opposed to tropical and temperate climates. Additionally, current adaptive standards suggest that adaptation can only happen during non-heating season or when cooling systems are not on. However, in many parts of the world, particularly in developing countries, school classrooms are free-running buildings with no heating (i.e. water pump, gas or electric) or cooling systems. Under these conditions, occupants may or may not find ways to adapt to have comfort. Research should look at extreme conditions (i.e., colder and hotter climate zones) in which there is an opportunity for passive strategies and energy savings.

From the literature review, it is also evident that there is a gap in knowledge on how different social backgrounds can influence the perception of comfort and indoor air quality expectations of children. Home conditions can also play a role in their expectations. Research should look at different school settings (i.e., private, private-subsidize or charter, and public schools) and see if their socioeconomic background can influence their perceptions and their adaptability responses.

This study seeks to contribute to the understanding of the thermal and indoor air perceptions of young children in the classrooms of school buildings in southern Chile. The study follows a field-survey methodology similar to the one used in adult surveys. However, it incorporates distinctive methodological approaches (e.g., questionnaire design that includes questions about clothing, and focus group interviews) that are better suited for a young age population. On the one hand, focus group interviews allowed for the capture of children's experiences that cannot get registered in a regular questionnaire or field observations. On the other hand, data collection was enhanced through the use of technology (i.e., touch screen tablets), which also proved to be useful at engaging students' participation. These improvements differentiate this study from traditional adult surveys.

The methods used in this dissertation will be discussed in the chapters 4 and 5, which are dedicated to present the results of two manuscripts. The first one was published in the conference proceeding for the Architectural Research Centers Consortium ***(ARCC) 2019 International Conference: Future Praxis Applied Research as a Bridge Between Theory and Practice***, at Ryerson University, Toronto, Canada, presented on May 29 to June 1, 2019. This publication focuses only on thermal comfort perceptions of children and teachers by analyzing physical classroom conditions in the fall and winter, in the city of Concepción. This includes a comparative analysis between children and teachers' TSV as well as differences found between different types of school (public, private-subsidize, and private-nonsubsidized).

The second manuscript, is an unpublished article that will soon be submitted to the international journal ***Building and Environment***. The article focuses on the analysis and results of children/teacher perceptions of thermal comfort and indoor air quality relative to their socio-economic background in naturally ventilated classrooms in primary schools. It provides in-depth methodology implemented in the study, which includes questionnaires design, data collection, and analysis developed for a field study in primary schools.

CHAPTER IV: RESULTS

THERMAL COMFORT AND AIR QUALITY IN CHILEAN SCHOOLS, PERCEPTIONS OF STUDENTS AND TEACHERS

The work was published in the conference proceeding for the Architectural Research Centers Consortium ***(ARCC) 2019 International Conference: Future Praxis Applied Research as a Bridge Between Theory and Practice*** at Ryerson University, Toronto, Canada, May 26, 2019.

I am the lead author of this study and my advisor; Professor Alison Kwok is the co-author for this publication, who contributed by reviewing the study design and analyses and providing editing. I designed study, conducted data collection and analyses, wrote, and presented this publication. This paper in its publishable form as it appears the conference proceedings.

This chapter reports on the findings of the analysis of thermal comfort perceptions of children and teachers by analyzing physical measurements of classroom conditions (i.e., air temperature, relative humidity, air velocity, radiant temperature, and CO_2 concentrations) in fall and winter, in the city of Concepción. Comparative analysis between children and teachers' TSV as well as differences between different types of schools (public, private-subsidized, and private-nonsubsidized) are presented.

4.1. Introduction

School buildings are one of the most critical environments because of the significant amount of time that children spend indoors at school and home during the developmental years of life. Closer attention needs to be paid to the indoor climate of classrooms, to promote comfort and well-being that support academic performance and user satisfaction. Young children are more susceptible to environmental pollutants than adults (Mendell & Heath, 2005). Higher temperature and poor ventilation have been identified as elements that create unfavorable effects on children's thermal comfort and performance, as shown in previous fieldwork studies (Bakó-Biró, Clements-Croome, Kochhar, Awbi, & Williams, 2012; Cui, Cao, Park, Ouyang, & Zhu, 2013b; Haverinen-Shaughnessy et al., 2015; Mendell et al., 2013). Thermal comfort of occupants in a given environment not only depends on physical parameters but also on the interaction of physiological and psychological factors. Children's physiological characteristics are different from those of adults (e.g. in office settings), which may influence their perception and thermal preference as shown in the literature (Montazami, Gaterell, Nicol, Lumley, & Thoua, 2017; ter Mors, Hensen, Loomans, & Boerstra, 2011; Zomorodian, Tahsildoost, & Hafezi, 2016, Mendell & Heath, 2005). Limited studies exist in which the perspectives of children and teachers regarding their perception of the indoor environment are combined in a single study.

In adaptive thermal comfort, "occupants are deemed as active agents in creating ideal indoor thermal conditions" (G. S. Brager & de Dear, 1998; Kim & de Dear, 2018a) through adaptive strategies such as opening windows. In classrooms however, school children have no control over windows, unless directed by a teacher. Additional clothing adaptations are limited because of dress code policies requiring student uniforms.

This study presents fieldwork results of thermal comfort and environmental perceptions of students and teachers in naturally-ventilated primary schools in Southern Chile. This study looks deeper at occupant perceptions of classroom environmental conditions, including thermal preferences as related to contextual factors such as a socioeconomic status (type of school, home conditions, and health-related symptoms). The study is guided by several research questions: (1) What are the physical conditions of classrooms in schools in Concepción city?; (2) Do expectations of comfort differ between students and teachers?; and (3) Do subjective perceptions of classrooms differ between the types of schools?

4.2. Methodology

4.2.1. Field Site Selection

The fieldwork includes subjective surveys with simultaneous measurements of classroom environmental conditions of schools in the metropolitan area of Greater Concepción (hereafter MACG) in the cities of Concepción and San Pedro de la Paz, at 36°S of latitude. The MACG is the biggest conurbation outside of Santiago (Chile's capital). Both cities were selected because of their proximity to the city center, similar climate conditions, the highest population of inhabitants, and the number of school buildings within the MACG (i.e., a total of 104 schools from the public, private-subsidized and, private-nonsubsidized sectors).

Climate conditions for Concepción and San Pedro de la Paz, based on the Köppen Classification System are temperate (*Csb*), with cold mild winters and mild dry summers. Using historical weather data from IWEC (ASHRAE-IWEC, 2001), the range of annual average temperature in Concepción is 13ºC (55.4ºF), an annual average minimum of 8ºC (46.4ºF), an annual average maximum of 18ºC (64.4ºF). The maximum temperature can reach up to 28ºC (83ºF) during the summer months (December through March) and the low temperature can reach -2ºC (28ºF) during winter (June through September). Relative humidity averages can range between 58% and 90%. Sky coverage for this location has an annual average mean of 49%, an average minimum of 18% and the average maximum of 75%. Predominant annual wind direction is from the southwest, and during winter months the predominant wind direction is from north to south with a wind speed of 20 m/s (67 ft/s).

4.2.2. School Selection and Classroom Description

Three types of schools exist in Chile: public, private-subsidized, and private-nonsubsidized. The differences among the three types are related to ownership, administration, socioeconomic level of the families, the index of vulnerability (IVE-SINAE index); developed by the government which measures the social vulnerability of students. This index is based on a set of criteria that allows identifying different groups of the populations of students in primary and secondary education according to the level of vulnerability they present. “Vulnerable” is classified into three hierarchy priorities: 1) socioeconomic risk, 2) socio-educational risk related school performance, attendance or desertion of the educational system, and 3) same socioeconomic risk as the second priority but without the socio-educational risk related. The IVE-SINAE can also provide subsidies for free breakfast and lunches, as well as other scholarships and government programs. The selection of the participating schools was based on their IVE index range: 100%-70% (IVE) for public school, 69%-20% (IVE) for private-subsidized and 19%-0% (IVE) for private-nonsubsidized schools. Previous studies on thermal comfort and environmental conditions in classrooms (Soto-Muñoz et al., 2015; Trebilcock et al., 2016b and Almeida et al., 2010), were performed in public school settings only. This study provides new research for other school types.

Nine schools participated in this study: four public, two private-subsidized and three private- nonsubsidized across Concepción and San Pedro de la Paz. For more detailed information, see table 1. The selection criteria included: 1) middle school grade levels (6th to 8th grade); 2) naturally ventilated classrooms; 3) no HVAC system and limited heating; 4) similar heavyweight structure (reinforced concrete or brick with seismic design provisions); 5) similar spatial configuration of classrooms; and 6) classroom space per student ≥ 1.1 m^2 (11.8 ft^2) (classroom density range of 30 to 45 students per classroom). From the nine schools, a total of 28 classrooms were surveyed during fall season, and 11 during winter season. All selected school buildings are multi-story, and surveys were conducted on different floors, depending on classroom location. The average floor area of the classrooms was 50.49 m^2 (543.46 ft^2), much smaller compare to recommend ASHRAE 62.1 (ASHRAE, 2016) occupant density 35/100 m^2 (35/ft^2).

4.2.3. Subjects

All subjects were from the local area of Concepción and San Pedro de la Paz with a few exceptions of immigrants from Brazil, Haiti, and Venezuela. The selection of middle school students for this study was motivated by the limited number of thermal comfort studies performed on primary schools. Also, in Chilean schools from first to eighth-grade levels, students spend all day in the same classroom versus other schools where the students might move to different classrooms for different subjects. Only the teachers move from one classroom to another. Therefore, groups of students spend a significant amount of time inside the same room, and are familiar with their indoor environment for the entire year. Middle schoolers, sixth through eighth grade, 10-14 years old (only exception is that there was one case of a 19-year-old), were chosen for their ability to understand questions and reasoning at that age.

Middle school teachers were also surveyed during the fieldwork at the same time of the students in order to compare their perceptions of the classroom conditions with student responses. Most classroom environments had one teacher, but in some cases, up to three teachers were present in each classroom (head teacher, student teacher, and/or a teacher specialized in learning disabilities).

A total sample size of 888 students and 58 teachers participated in the field survey campaign in the fall season (April and May): 426 males (~48%) and 462 females (~52%). In the winter season, 333 students and 23 teachers participated (July and August): 173 males (~52%) and 160 females (~48%).

4.3. Data Collection

4.3.1. Ethical and Responsible Conduct Research

Approval was obtained by the Institutional Review Board (IRB) for research involving human subjects, from both the University of Oregon and the Universidad de Concepción, prior to the start of data collection.

4.3.2. Measurements of Indoor and Outdoor Environmental Parameters

Measurements of indoor and outdoor environmental parameters were obtained: classroom thermal and air quality measurements were taken during the same time as the surveys were administered. In accordance with standards: ISO 7726 "Ergonomics of the thermal environment Instruments for measuring physical quantities" (ISO 7726, 2001) and ASHRAE 55-2017 "Thermal Environmental Conditions for Human Occupancy" (ASHRAE, 2017), a Testo 480 data logger, with indoor probes were used to collect ambient air temperature, relative humidity, airspeed, radiant temperature (globe thermometer with a diameter = 150mm), and CO_2 concentration levels. Dylos DC1700 sensors for particle counts at $PM_{2.5}$ and PM_{10} were used. Each parameter was measured at the height of 1.1m (3.6 ft.) above the floor level based on the recommendations of ISO 7726 (ISO 7726, 2001) and ASHRAE 55 (ASHRAE, 2017). Outdoor environmental conditions, such as temperature, relative humidity, CO_2, and $PM_{2.5}$ and PM_{10} were also collected for the duration of the study from a local weather station at one of the school sites in Concepción.

For clothing insulation, the checklist from ISO 7730 (ISO 7730, 2005) and ASHRAE 55 were used to match CLO levels of Chilean students uniforms and teachers' outfits. For metabolic rate, the students were mostly seated, doing writing or light work, and estimated as "nearly sedentary," equivalent to 1.2 met (70 W/m^2 or 22 $Btu/h*ft^2$), according to ISO 7730.

4.3.3. Survey Questionnaire

Multiple versions of the survey questionnaire were checked with an external assistant teacher and university professors to ensure that it was suitable for the age group. The survey design included the use of emoji images and colors for the different scales, as other studies have done (Shamila Haddad, Osmond, & King, 2017b; Teli et al., 2013; Trebilcock et al., 2017b). This survey allowed the students to take the survey on a touch-sensitive interface using tablet devices. Offline software (Qualtrics) was used to collect responses. Use of these devices greatly supported engaging the students in the activity, raising interest and participation. The survey was conducted in Spanish; therefore, the scales and questions were translated into that language by the researcher. Prior to carrying out the actual surveys, pilot studies were conducted in order to ensure the proper functioning of tablets, gather feedback on the clarity of the questions, and prepare for logical administration of the surveys.

The questionnaire consisted of five parts: 1) current status of thermal comfort, air movement, and air quality using thermal sensation vote (TSV), air quality sensation vote (AQV), preference and acceptability. This section also included clothing questions regarding items worn during the class visits; 2) personal satisfaction about home and classroom environmental conditions, health-related symptoms experienced in the past; 3) house conditions; 4) impacts of environmental factors on classwork; and 5) general demographic information. For this paper, results from a portion of section 1 are presented, since data analyses for the other sections are currently in progress.

Survey questionnaires were administered 20 to 30 minutes after students/teachers had settled in their classroom environments. Specific classroom times were selected for visits, to avoid time periods when students had PE class on the day of the survey, to minimize higher activity levels. Measurements were collected during two classroom visits in the same day (morning 8:30–11:30 am and afternoon 1:00–4:30 pm respectively) during fall and winter season. The field study used a longitudinal survey approach, the same classrooms and students were surveyed in both seasons. Because of school academic schedules (ending first semester and winter break) in June and July months, the study was conducted in four schools only during the winter season, instead of all nine in the first campaign. It is important to note that these four schools had the same participating subjects from the first field study during fall, with minor changes due to newly registered students or withdrawn students from the classroom.

4.4. Results

4.4.1. Assessments of Physical Environmental Measurements

During the field study campaigns in fall, the average outdoor dry bulb temperature was 12.5ºC (54.5ºF) for April and 11.6ºC (52.9ºF) for May, with a minimum temperature of 8.5ºC and a maximum of 18ºC. The lowest temperature was registered early in the morning between 5, and 6 am, whereas the highest temperature was reached around 2 to 3 pm, just before school release. The mean indoor air temperature (Ta) of classrooms was 19.9 ºC, with a maximum of 23.8 ºC and a minimum of 16.5ºC during fall. The mean indoor relative humidity (RH) was 65.8% with a range of 42%–85%. In winter, the average outdoor temperature ranged between 9 and 10ºC during July and August, with a minimum temperature of 5.6ºC and a maximum of 15ºC, respectively. Classroom average indoor air temperature in winter was 18.8ºC, with a minimum of 15.0ºC and a maximum of 23.8ºC. Public schools registered the highest mean value of relative humidity of 75.3%, in winter and a maximum of 85% during fall. However, in winter the maximum of 85% was measured in Private-subsidized. High levels of CO_2 was also recorded with a mean average of 1625 ppm and a maximum of 3330 ppm in Public schools during fall. However, CO_2 average levels of 2066 ppm and the maximum of 3580 ppm in Private-nonsubsidized during winter. The high mean indoor air temperature was registered in Private-subsidized schools with an average of 22ºC and maximum of 24ºC. Low mean indoor temperatures were measured in Public school of 16.5ºC during fall and of 15ºC in Public and Private-nonsubsidized schools. It is important to note that air velocity in all classrooms during visits was very low, almost imperceptible, with an average of 0.09 m/s in fall and winter and a maximum of 0.16 m/s. Due to low outdoor temperatures, windows were mostly closed. In all surveyed schools, they rely solely on operable windows for air renovation, since there is no mechanical system or use of fans in any of the classrooms. High concentration levels of CO_2 were measured across all schools, with maximum concentrations of 4,326 ppm in winter in public schools and a minimum of 858 ppm in fall in private-subsidized schools. Average CO_2 ranges between 1,600-1,900 ppm, more than 1,000 ppm above outdoor levels (average ~500 ppm).

The operative temperature (Top) for this study was calculated as the average of the air temperature (Ta) and the mean radiant temperature (MRT), as specified in ASHRAE 55 (ASHRAE, 2017). For prevailing mean outdoor air temperatures, an exponentially weighted running mean temperature was used based on the studies of Humphreys (Humphreys & Nicol 1998; Humphreys and Nicol 2002) and ASHRAE 55 (ASHRAE, 2017). An exponentially weighted mean temperature puts more weight on temperatures from days closer to the current one, as noted by Nicol and Humphrey (Humphreys & Nicol, 1998). People's responses depend heavily on their immediate thermal history. As seen in

Figure **4.1**, indoor operative temperature plotted in ASHRAE 55-2017 adaptive chart, ranging from ~7.5 to ~11 ºC, falls outside the comfort zone. Only at the beginning of the study (April) temperatures were inside the comfort zone**.**

Table 4.1 Summary of classroom visits, building details, sample size, and number of surveys for different seasons

School type	No. of classroom surveyed	No. of floors surveyed	Average height of classroom (m)	Average floor area of classroom (m^2)	Classroom seating capacity (n of tables)	Classroom density area/n students (m^2)	Fall survey campaign: Sample size (N)		Fall survey campaign: Total number of surveys (ns)		Winter survey campaign: Sample size (N)		Winter survey campaign: Total number of surveys (ns)	
							Students	*Teachers*	*Students*	*Teachers*	*Students*	*Teachers*	*Students*	*Teachers*
Public	14	2, 3	3.25	47.81	30–35	1.36	386	32	762	36	72	5	141	7
Private-subsidized	6	2, 4	2.95	60.45	40–45	1.34	202	8	332	8	206	13	392	13
Private-nonsubsidized	8	2, 3	3.02	43.21	25–30	1.44	300	18	448	18	55	5	109	5
Average			3.07	50.49		1.38								
Total	28						888	58	1542	62	333	23	642	25

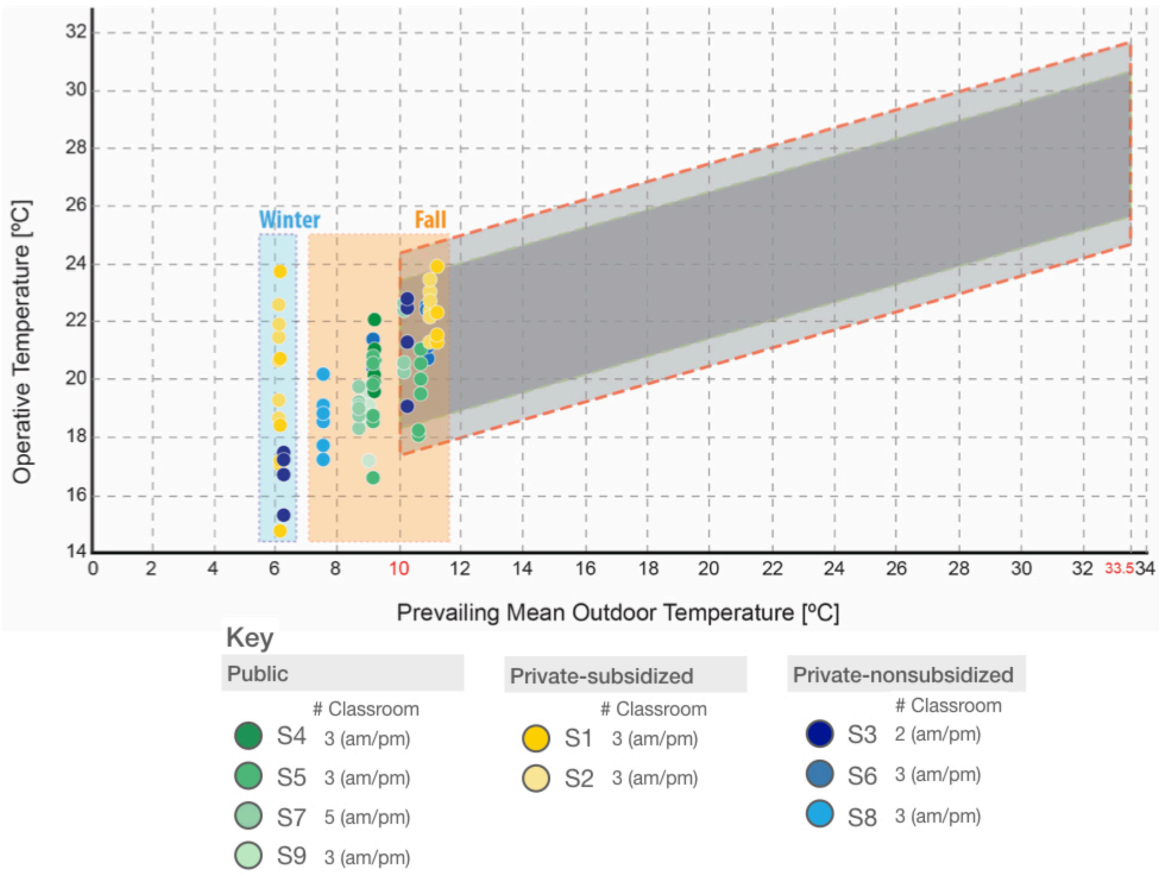


Figure 4.1. ASHRAE 55–2017 adaptive comfort zone for naturally ventilated spaces fall and winter season. Indoor operative temperature is plotted against prevailing mean outdoor temperature for all the 28 classroom surveyed. Orange zone represents fall and blue zone winter conditions. Each point represents an individual classroom indoor operative temperature per survey assessment taken twice a day (morning and afternoon) for a single day visit at each school. During fall it can be seen that 50% of the points fall inside the comfort zone within 80 to 90% acceptability range. In winter however all points fall outside the comfort zone.

4.4.2. Thermal Sensation Votes and Preferences

Results in Figure 4.2 and Figure 4.3 show approximately 80% of the teachers and students voted their thermal sensation primarily within the three central categories of the scale (-1, 0, +1). The mean TSV for students is 0.92 (SD 1.15) in fall and -0.4 (SD 1.27) in winter; for teachers, mean TSV 0.03 (SD 1.0) in fall and -0.28 (SD 1.37) in winter were found.

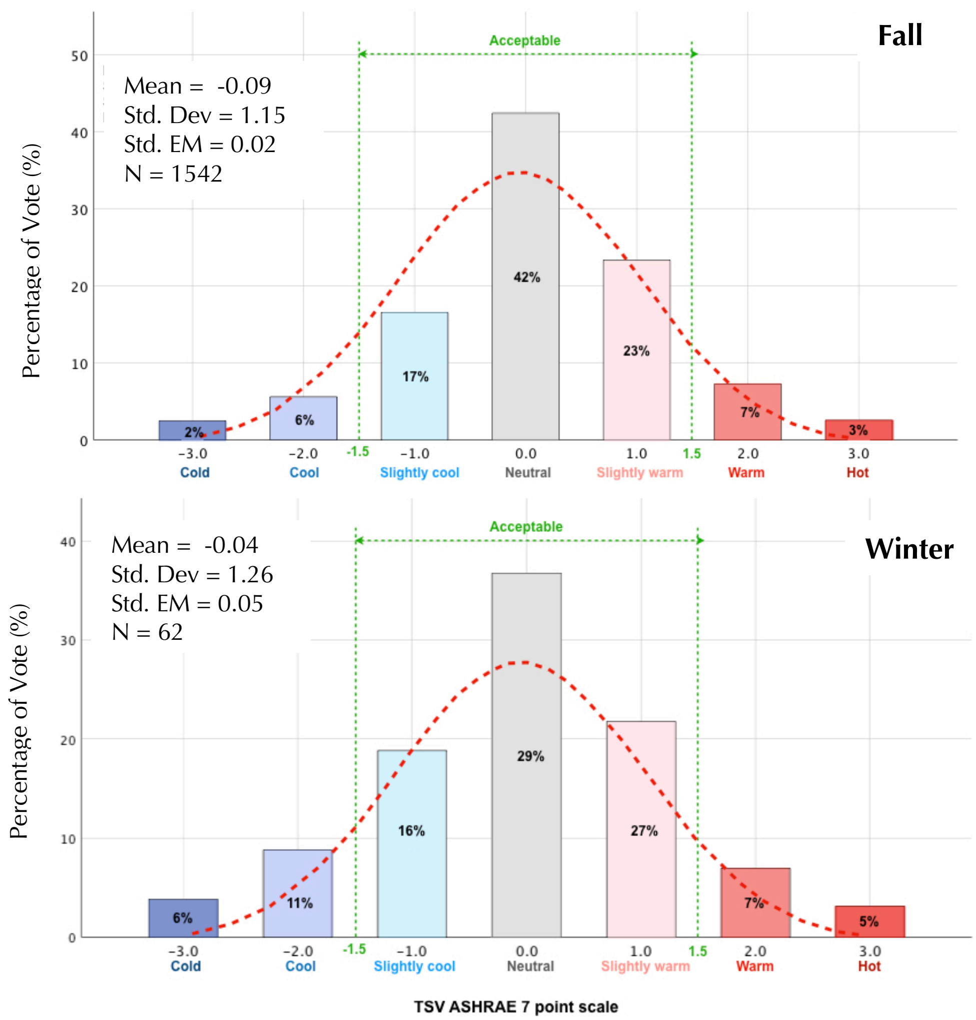


Figure 4.2. Student thermal sensation vote in fall (top) and winter (bottom). Normal distribution TSVs for student in all schools, based on ASHRAE 7-point scale. Std. Dev = standard deviation, Std. EM = standard error of the mean. Acceptable is the percentage satisfied occupants using ASHRAE TSV 7-point scale is within = -1.5 ≤ acceptable ≤ +1.5 (when using a scale resolution of 0.5). For the study, surveys included a scale resolution of 0.5, but after analysis, these values were combined into integers.

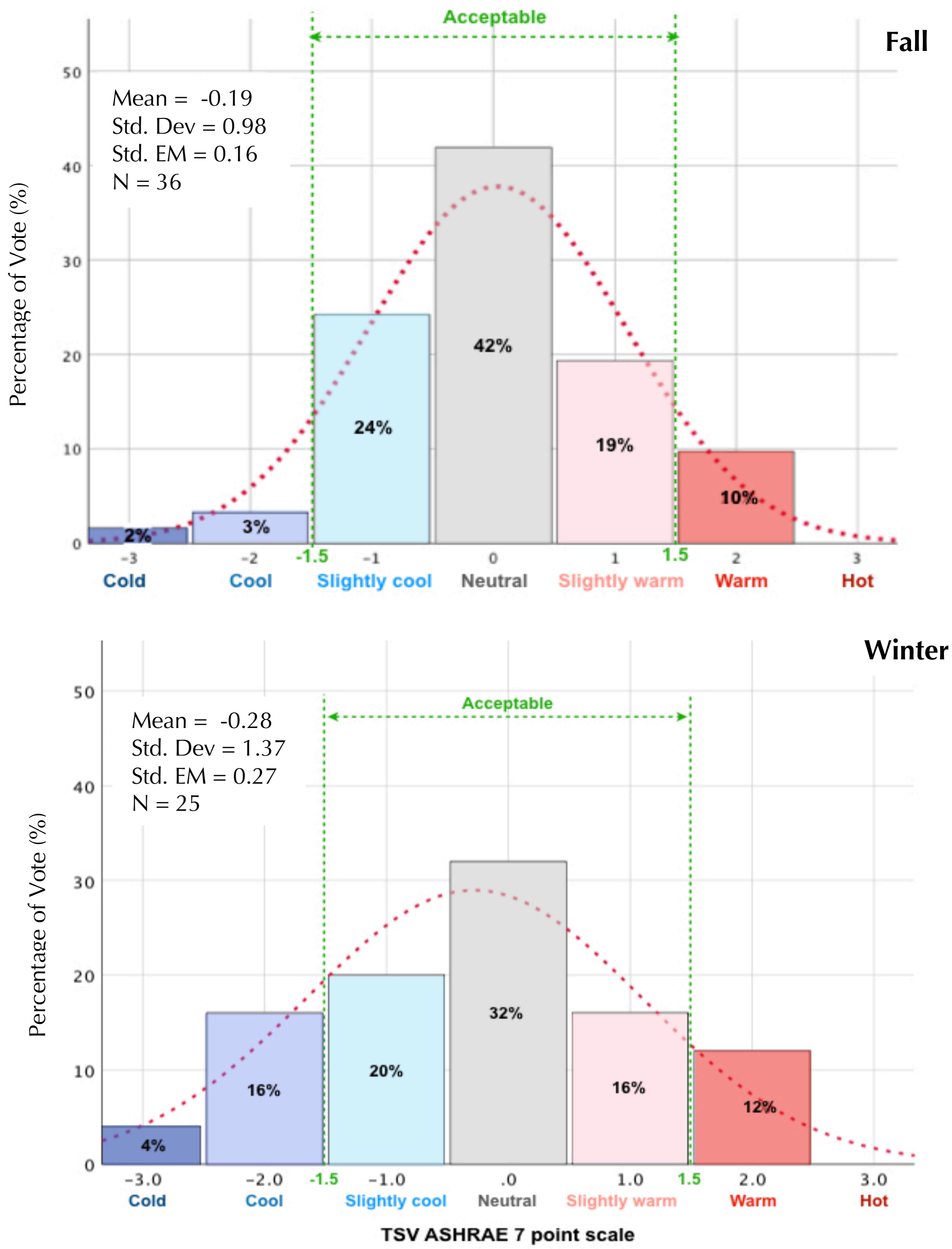


Figure 4.3. Teacher thermal sensation vote in fall (top) and winter (bottom). Normal distribution of TSVs for teachers in all schools, based on ASHRAE 7-point scale. Std. Dev = standard deviation, Std. EM = standard error of the mean. Acceptable is the percentage satisfied occupants using ASHRAE TSV 7-point scale is within = -1.5 ≤ acceptable ≤ +1.5 (when using a scale resolution of 0.5). For the study, surveys included a scale resolution of 0.5, but after analysis, these values were combined into integers.

Comparing the thermal sensation votes for students and teachers, across types of schools during fall as seen in Figure 4.4 similar distribution patterns occur with slight shifts towards the warm side of the thermal sensation scale for students and the cool side of the scale for teachers, as seen in Figure 4.5. For students, there are small differences between school types, except for private-subsidized which showed a slight shift toward a warm thermal sensation, corresponding to higher indoor temperature measured in those classrooms, Figure 4.4.

Regarding their thermal preference (TPV), corresponding to the question “how would you prefer the temperature of your classroom?”, Figure 4.5 more than 50% of both teachers and students preferred “no change.”

4.5. Conclusions

Primary school children, aged 10-14, were capable of understanding thermal sensation and preference rating scales, and their responses are similar to adult responses. The distribution of thermal sensation votes for student and teacher, more than 80%, fall within the three central categories of the scale (-1, 0, +1) of the ASHRAE thermal sensation scale during the fall season. However, in winter 68% (students) and 72% (teachers) votes are concentrated in three central categories, suggesting the consistent responses between students and teachers across all schools. Teachers’ thermal sensation had a slight tendency towards slightly cold scales, which can correspond to their lower metabolic rate compared to students whose tendency was towards slight warm scales.

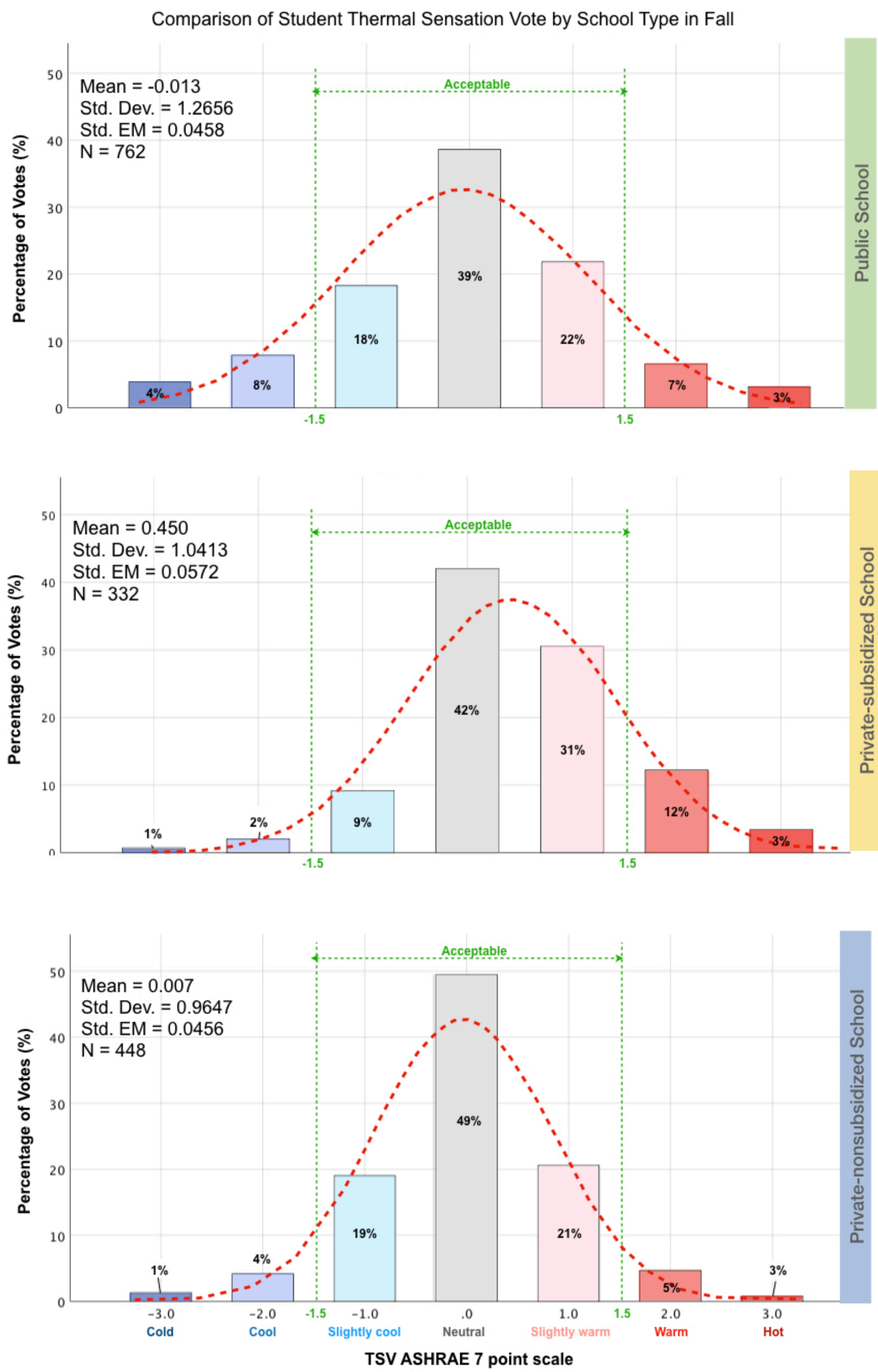


Figure 4.4. Comparison of students thermal sensation votes (TSVs) normal distributions for different schools type during fall. Top: public schools; center: private-subsidized; bottom: private-nonsubsidized. Std. Dev = standard deviation, Std. EM = standard error of the mean.

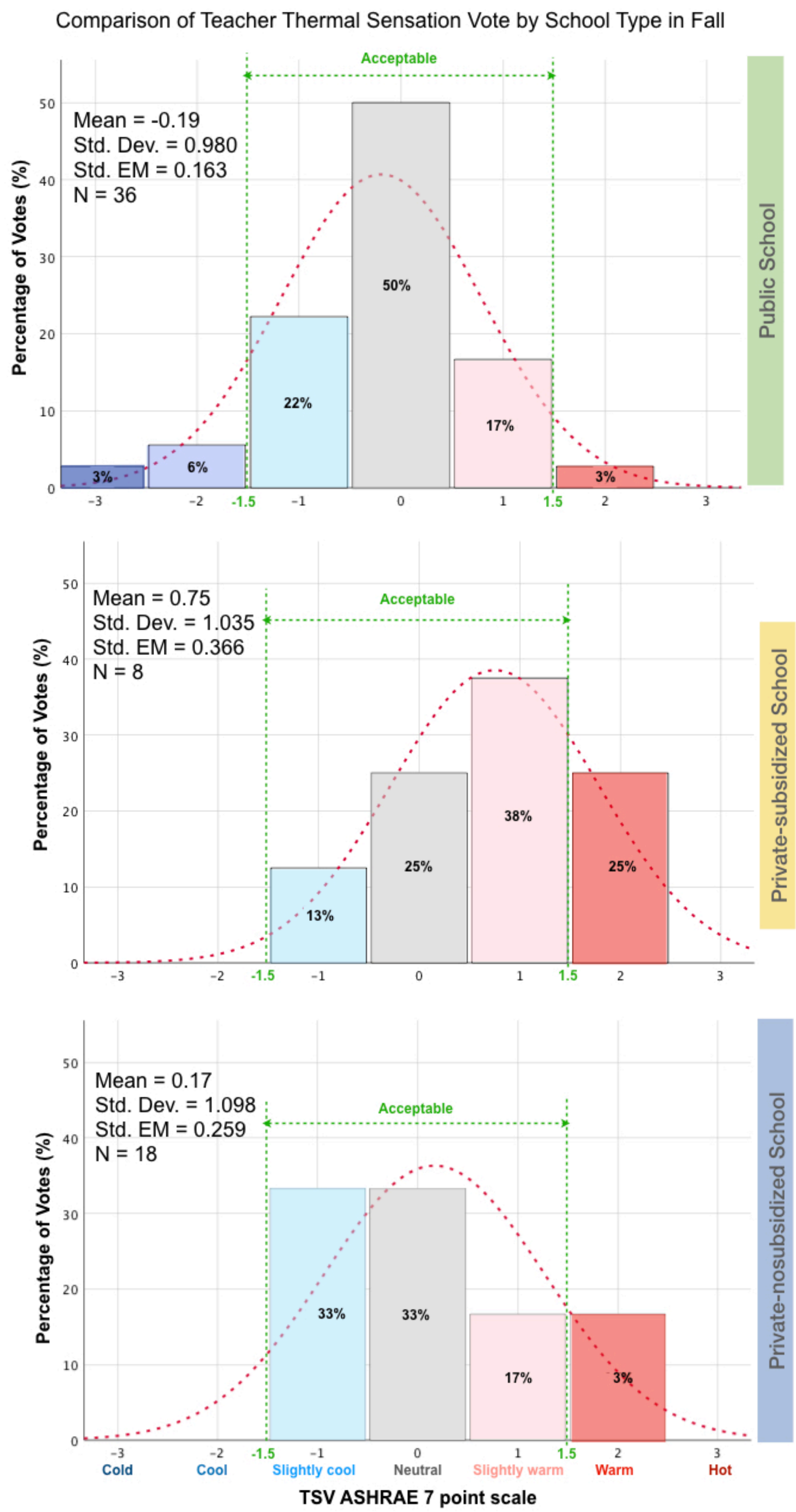


Figure 4.5. Comparison of teachers thermal sensation votes (TSVs) normal distributions for different schools type during fall. Top: public schools; center: private-subsidized; bottom: private-nonsubsidized. Std. Dev = standard deviation, Std. EM = standard error of the mean.

The perceptions of the students across different school types do not show a significant difference. A small distinction can be seen during the fall season for private-subsidized schools with a small tendency towards a warm thermal sensation, which is corroborated by the measured indoor temperatures compared to other schools. The latter suggests that students can perceive the conditions of their classroom based on the physical measurements collected.

Air quality across all schools was poor, with very high concentrations of CO_2 levels due to high-density classroom and little air movement (i.e., windows were mostly close), which limits the air ventilation. Thus, affecting the performance of students by feeling tired and difficulty concentrating at the end of each period. Also, high percentages of relative humidity across all school types, in some cases presence of mold, can have a more significant impact on health and well-being of students and teachers, thus suggesting new strategies need to be implemented through better architectural design, that can improve indoor classroom conditions.

CHAPTER V: RESULTS

INFLUENCE OF SOCIAL BACKGROUND AND CLASSROOM CONDITIONS ON PERCEPTIONS OF INDOOR AIR QUALITY IN CHILEAN SCHOOLS

The work is an un-published article that I plan to submit to the international journal ***Building and Environment***.

I am the lead author of this study and Professors Alison Kwok, Alexandra Rempel, Kevin Van Den Wymelenberg and Charles Martinez, are co-authors for this publication. My dissertation committee has provided feedback on statistical analyses, suggestion for graphic presentation of data, and proofreading. I designed study, conducted data collection and analyses, and wrote this publication.

This chapter focuses on the analysis and results of children/teacher perceptions of thermal comfort and indoor air quality, and how children's' perceptions relate to their socio-economic background in naturally ventilated classrooms in primary schools. It provides in-depth methodology implemented in the study, which includes questionnaire design, data collection, and analysis for a field study in primary schools.

5.1. Introduction

During children's developmental years of life, from early childhood to adolescence from 2 to 24 years of age (i.e., from pre-kindergarten to university or college), students spend significant time indoors 80–90% between classrooms and the home (Mendell and Heath, 2005; Singh; Klepeis et al., 2001). School learning environments are one of the most critical spaces where a different aspects of sustainability research can be considered such as indoor environmental quality, energy efficiency, performance, behavior, health, and well-being because of the amount that students spend inside a classroom.

Learning activities demand high levels of concentration, therefore, classroom design characteristics should provide a stimulating environment that promotes learning process (Guili et al 2012; Mishra and Ramgopal, 2015; Turunena et al, 2014). However, studies have shown that elevated classroom temperatures (de Dear et al, 2013; Mendell and Heath, 2005; Wargocki and Wyon, 2007 and 2012) high CO_2 levels, and low ventilation rates (Bakó-Biró, Clements-Croom, Kochhar, Awbi, & Williams, 2012, Cui et al. 2013; Haverinen-Shaughnessy et al. 2015; and Mendell et al. 2013) can have negative impacts on student performance and well-being. Particularly in developing countries, such as Chile, unfavorable environmental conditions (i.e., high temperatures, RH, and CO_2 concentrations) have been identified (Soto, Trebilcock, & Pérez, 2015), where there is no adherence to indoor environmental quality standards.

Young children are more susceptible to environmental pollutants than adults (Mendell and Heath, 2005). Closer attention needs to be paid to the existing indoor climate of classrooms, to promote comfort and well-being that support academic performance and user satisfaction. However, there is limited information about children's environmental perceptions and what conditions are considered acceptable to them (Teli, James, & Jentsch, 2013). Additionally, it is essential to understand the physical conditions of air quality that children are exposed to, particularly in crowded free-running (i.e., no cooling systems and limited heating in some private schools) classrooms. This study tackles these issues in-depth as few studies exist with this demographic.

The perception of thermal comfort in a given environment not only depends on physical conditions but also on the interaction of physiological, psychological, emotional, cultural, and social factors (Fabbri, 2015). Current standards such as ASHRAE 55, ISO 7730, EN10552, and ISO EN10551, define acceptable ranges of operative temperature in school classrooms, based on heat balance and the adaptive thermal comfort models, on studies done in climate chambers simulating office environments with adult occupants only. Results from these studies are not necessarily transferable to thermal sensations and preferences of school children (Shamila Haddad et al., 2019; Mors et al., 2011; Teli, Jentsch, James, & Bahaj, 2012) . Due to the absence of standards that deal specifically with indoor environmental quality in educational building and classroom spaces at different grade levels, architects and engineers must use current applicable standards.

Recent studies have shown that children's perceptions and thermal preferences differ from those of adults because of their physiological characteristics and because of the office settings of the studies (Montazami, Gaterell, Nicol, Lumley, & Thoua, 2017; Mors ter, Hensen, Loomans, & Boerstra, 2011; Zomorodian, Tahsildoost, & Hafezi, 2016, Mendell & Heath, 2005). In particular, children have higher resting metabolic rates (i.e., 88.25 W/m^2) than adults (i.e., 70 W/m^2 (Holliday, 1971, as cited in Teli at al., 2013), potentially having an impact on their abilities to detect temperature changes accurately. However, studies have explored the relations of PMV and TSV with different resting metabolic rates (RMR) for children based on PMV predictions, ranging from 48.8 W/m^2 (MET=1.4) to 58.15 W/m^2 (MET = 1.1), which are values that are consistent with actual student votes (Shamila Haddad, Osmond, & King, 2013). School classrooms also differ from office settings in that students have multiple activities within their classrooms ranging from reading/studying to more active hands-on activities. In addition, the density (30 to 40 students per classroom) is quite high compared to U.S. classrooms; and students have opportunities 3 to 4 times a day for outdoor playtime. Therefore, the daily routine of a student is much more active than a typical office employee, influencing their perception of thermal comfort (Teli at al., 2013). Limited studies exist (Kwok, 1997) where the perspectives of children and teachers regarding their perception of the indoor environment are combined in a single study.

In adaptive thermal comfort theory, Brager and de Dear (1998) argue that "occupants are deemed as active agents in creating ideal indoor thermal conditions" (as cited in Kim and de Dear 2018) through adaptive strategies such as opening windows. In Chilean classrooms, however, school children have no control over windows, unless directed by a teacher. Additionally, Chilean school dress code policies require students to wear uniforms, with limited opportunity to modify clothing throughout the day.

This study presents fieldwork results of thermal comfort and environmental perceptions of students and teachers in naturally-ventilated primary schools in Southern Chile. This study looks at contextual factors such as socio-economic background (the type of school, vulnerability index, and home conditions) that can influence subject's perceptions of classroom environments.

The investigation aims to evaluate whether perceptions of students of thermal and air quality comfort are related to their social and/or economic background. Several research questions guide the study: (1) What are the physical conditions of classrooms in the city of Concepción?; (2) Do expectations of comfort differ between students and teachers?; and (3) Do subjective perceptions of classrooms differ between the types of schools that represent different social/economic backgrounds?

The first part of this paper examines the physical conditions of primary school classrooms by different school type and to determine whether significant differences exist. The second part evaluates if expectations differ between students and teachers. Finally, in the third part of this paper the subjective perceptions of students and teachers are examined between school types.

5.2. Methodology

Two field studies were conducted in primary school classrooms in the Metropolitan Area of Greater Concepción (hereafter MACG) in the Chilean fall and winter in 2018. A longitudinal survey approach was used, consisting of real-time subjective responses with simultaneous physical measurements of thermal comfort and air quality in nine free-running classrooms (i.e., no ventilation system and no heating systems present, in only a few cases heating system). The main form for fresh air circulation is only by opening windows and doors. Two field campaigns were conducted: first, for surveys conducted outside the heating season (i.e., no heating or cooling system on) and during the heating season (i.e., only in private schools heating systems was present and on).

Most Chilean schools function in “free-running mode” and do not adhere to any indoor environmental quality standard because there is no Chilean law that compels them to do so. In fact, no standard, such as ASHRAE 55 or ISO 7730, exists in Chile. The implementation of any available international standard turns out to be a slow and expensive process in developing countries. Most schools do not have heating or cooling systems due to exorbitant associated costs. Chilean educational investment capital is limited and in many cases, there are no budgets to cover such operational costs. The “National Decree” or rule of law (Decreto Supremo DS 548, in Spanish) only requires heating systems for locations south of latitude 36ºS (Trebilcock, Soto, Yañez & Figueroa, 2016b), well south of the bulk of the population, and sets a minimum temperature of only 12ºC inside a classroom. In addition, there are no temperature guidelines for cooling systems or passive strategies even for climate zones with relatively cold winters or hot summers. Thus, the Chilean classroom represents a very passive and free-running mode of buildings.

5.2.1. Field Study Location

Field studies were performed in the cities of Concepción and San Pedro de la Paz in southern Chile, at 36º49′ South Latitude, 73°2' West longitude and 15 meters above sea level, see Figure 5.1. The total population of Concepción is 223,574, and of San Pedro de la Paz is 131,808 (INE Censo, 2017).

Climate conditions for Concepción and San Pedro de la Paz are temperate with cold mild winters and dry mild summers, based on a rating of *Csb* on the Köppen-Geiger Climate Classification System (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), which represents: a warm temperate climate (C); with warm (b) and dry summers (s). Using historical weather data from IWEC (ASHRAE-IWEC, 2001), Concepción has 1913 heating degree–days (HDD) at a base temperature of 18.3ºC, with an annual average temperature of 13ºC (55.4ºF), an average minimum of 8ºC (46.4ºF), and an average maximum of 20ºC (64.4ºF). The maximum temperature can be as high as 28ºC (83ºF) during the summer (December through March), and the low temperature can reach -2ºC (28ºF) during winter (June through September). Precipitation is concentrated during the winter months, with an annual rainfall of 1200 mm (50 inches), for reference see Figure 5.2. Relative humidity averages can range between 58% and 90%. The predominant annual wind direction is from the southwest, and during winter months the predominant wind direction is from north to south with an average wind speed of 20 m/s (67 ft/s).

These cities were selected because of their close proximity, similar climate conditions, the high population of students and teachers with respect to other cities, in addition to the number of school buildings available for this study (i.e., a total of 104 schools). The latter provides a more complete sample of school building types, with a wide range of social and economic backgrounds, than in other cities.

5.2.2. Buildings Surveyed: Types and Characteristics

In Chile, three types of school categories exist: public, private-subsidized, and private-nonsubsidized. The differences between the three types are related to ownership, financing, and administration (MINEDUC, 2016). A municipality administers public school operations and receives subsidies from the State. Private-subsidized schools are administered by private organizations that receive public subsidies from the State per student of the same amount as public schools (i.e., voucher), for its operation. Private organizations administer private-nonsubsidized schools and do not receive public subsidies, as well as being financed only via tuition. For both public and private-subsidized schools, the subsidy system is based on student attendance (Santiago, Fiszbein, García Jaramillo, & Radinger, 2017). Student attendance greatly depends on family income levels (Santiago, et al., 2017). Most disadvantaged families attend public schools; private-subsidized schools, on the other hand, receive a wider socioeconomic range of students from different backgrounds (middle to middle low income), and private non-subsidized schools are mostly attended by students from high-income families (Santiago, et al., 2017).

Figure 5.1. Map of Chile, with its 13 regions. In red: VIII Region of Bio–Bio and locations of Concepción and San Pedro de la Paz with respect to region limits.

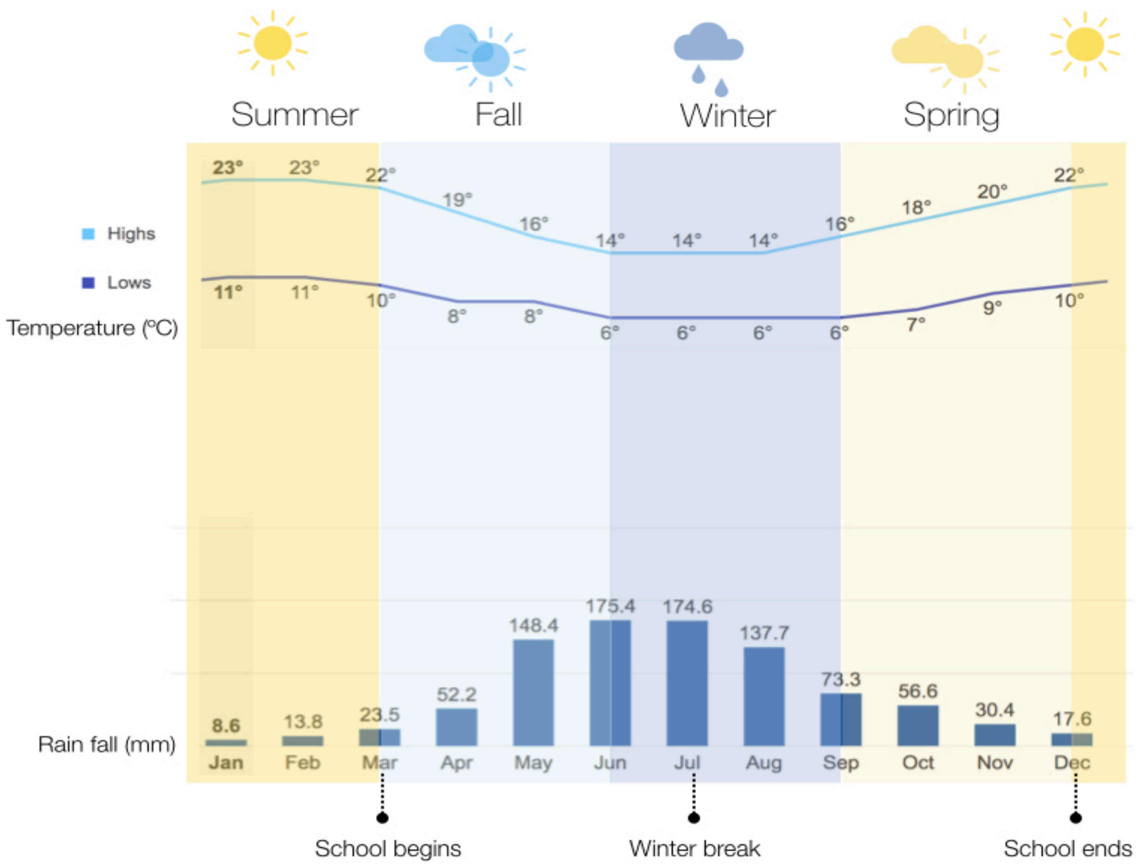


Figure 5.2. Concepción weather averages temperature (ºC) and rainfall (mm), with academic school year. School starts first week of March, and first semester ends in mid-July. Second semester starts third week of July and last until mid-December.

The criteria used to select the nine case studies investigated originated to determine whether differences in schools might be due to different socioeconomic levels, based on the three main categories of schools present in Chile. The educational system in Chile is very socially segregated. The access to good quality education is more common in private schools than in public schools. This came about after the 1980's reform, in which a competitive voucher system for education was adopted. This included the state transfer of administration of public education to local municipalities, allowing public and private schools to have access to government funds, similar to charter schools in the US. Private-subsidized school grew from 18.5% in 1980 to 60% by 2012.

The index of vulnerability (IVE-SINAE index), developed by the government, measures the social vulnerability of students, and it was used to select public and private-subsidized schools participating in this research. The vulnerability index is based on a set of criteria that allows for the identifying of different groups of student populations in primary and secondary education, according to their level of vulnerability. "Vulnerable" is classified into three (decreasing) hierarchical priorities: 1) students with high socio-economic risk; 2) students with lower socio-economic risk but also present socio-educational risk related to school performance, attendance or desertion of the educational system; and 3) same socio-economic risk as the second priority but without the socio-educational risk (JUNAEB, 2019). The IVE-SINAE can help identified priorities in terms of how the State allocates subsidies for free breakfast and lunches, as well as other scholarships and government programs.

The IVE-SINAE index ranges from 100% to 70% of vulnerability for public schools, and from 69% to 20% for private-subsidized schools. Private-nonsubsidized schools do not get assigned an IVE index. Previous studies on thermal comfort and environmental conditions in classrooms in Chile (Soto-Muñoz et al., 2015; Trebilcock et al., 2016b and Almeida et al., 2010), were performed in public school settings only. This study contributes with new knowledge by adding the two other categories of private school types.

Nine schools participated in the field study during the fall season and four in the winter season, shown in Table 5.1and Figure 5.1 shows the location the metropolitan area of Concepción, and the city of San Pedro de la Paz. Both cities provide a wide range of socio-economic levels for school types. Considerations were taken for similar contextual characteristics such as location in urban settings, and similar architectural design. Additionally, a similar IVE-SINAE index was selected between school types in order to perform a comparative analysis within the three categories.

The selection criteria in term of building characteristics included: 1) middle school grade levels (6th to 8th grade); 2) free-running classrooms; 3) no HVAC or ventilation system and limited space heating; 4) similar heavyweight structure (reinforced concrete or brick with seismic design provisions); 5) built within similar decades (1990s and 2000s); 6) similar spatial configuration of classrooms; and 7) comparable classroom space per student: ≥ 1.1 m^2 (11.8 ft^2) (classroom density range of 30 to 45 students per classroom). From the nine schools, a total of 28 classrooms were surveyed during the fall season, and 11 during the winter season. All selected school buildings are multi-story, and surveys were conducted on different floors, depending on classroom location.

5.2.3. Subject Description

Participating subjects for this study included middle school children age 10–14 years old, sixth through eighth grade, as well as middle school teachers. The selection of middle school students for this study was motivated by the limited number of thermal comfort studies performed on primary schools as well as their ability to understand questions and reasoning at that age. Also, in Chilean schools from first to eighth-grade levels, most subjects are taught in the same classroom environment for the duration of the day, so students spend most of the day in the same classroom for an entire academic year. The latter is a much different condition from that seen in other school contexts such as the US, where students move to different classrooms for each subject and the teacher remains in "their" classroom. Instead, Chilean primary school teachers are the ones that move from one classroom to another to teach their subjects. Therefore, these groups of students are familiar with their classroom conditions as they spend a significant amount of time inside the same room, experiencing changes in their environment, seasonally for an entire year and from morning to afternoon.

Table 5.1 Summary of participating schools, surveys, and subjects

	Total	Public	Private-subsidized	Private-nonsubsidized
N Schools	**9**	4	2	3
N Classroom	**28**	14	6	8
Fall				
Sample size (students)	**888**	386	202	300
Sample size (teachers)	**58**	32	8	18
Survey responses (students)	***1542**	762	332	448
Survey responses (teachers)	***62**	36	8	18
Winter				
Sample size (students)	**333**	72	206	55
Sample size (teachers)	**23**	5	13	5
Survey responses (students)	***642**	141	392	109
Survey responses (teachers)	***25**	7	13	5

* Students responses were collected twice in the day for each classroom visit during the fieldwork. This explains why the survey responses are more than the sample size. Teachers, in some cases, were surveyed twice in the day, because their subjects matched more than one of the classrooms surveyed during that visit.

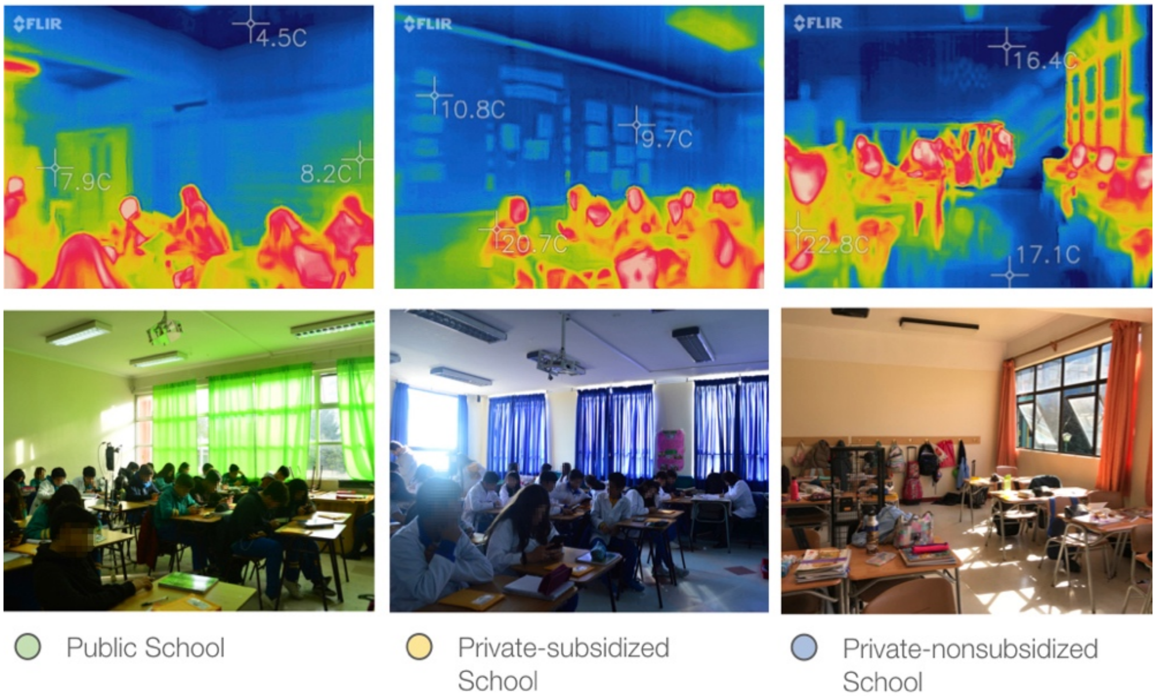


Figure 5.3. Case study of school classrooms surveyed. Images on top show surface temperatures, bottom existing conditions from public to private–nonsubsidized.

Student and teacher survey responses were collected at the same time in order to compare their perceptions of the same classroom conditions. Most classroom environments had one teacher, but in some cases, up to three teachers were present in a classroom (head teacher, student teacher, or a teacher specialized in learning disabilities).

A total sample size of 888 students (426 males ~48% and 462 females ~52%) and 58 teachers (426 males ~48% and 462 females ~52%) participated in the field survey campaign in the fall season (April and May). A total set of 1604 responses were obtained from students and teachers.

In the winter season, 333 students (173 males ~52% and 160 females ~48%) and 23 teachers participated (July and August). In winter a total set of 667 responses were collected from students and teachers.

5.2.4. Classroom Indoor Climate: Instrumentation and Procedures

Physical measurements of indoor environmental parameters were obtained in each classroom during both morning and afternoon visits. Thermal comfort and indoor air quality measurements were collected concurrently with the survey. In accordance with standard ISO 7726, "Ergonomics of the thermal environment Instruments for measuring physical quantities" (ISO 7726, 2001) and ASHRAE 55-2017, "Thermal Environmental Conditions for Human Occupancy" (ASHRAE, 2017), a Testo 480 data logger, with indoor probes, was used to collect ambient air temperature (T_a), relative humidity (Rh), airspeed (Va), radiant temperature (Tg) (globe thermometer with a diameter = 150mm), and CO_2 concentrations. Dylos DC1700 sensors for particle counts were used for $PM_{2.5}$ and PM_{10}. Each parameter was measured at the height of 1.1m (3.6 ft.) above the floor level and placed at the center of each classroom, based on the recommendations for Class-II protocol of ASHRAE 55 (ASHRAE, 2017).

Outdoor environmental parameters, such as air temperature, relative humidity, CO_2, and $PM_{2.5}$ and PM_{10} were collected from a local weather station located at one of the school sites in Concepción. Table 5.3 and Table 5.4 summarize the key classroom indoor environmental parameters measured.

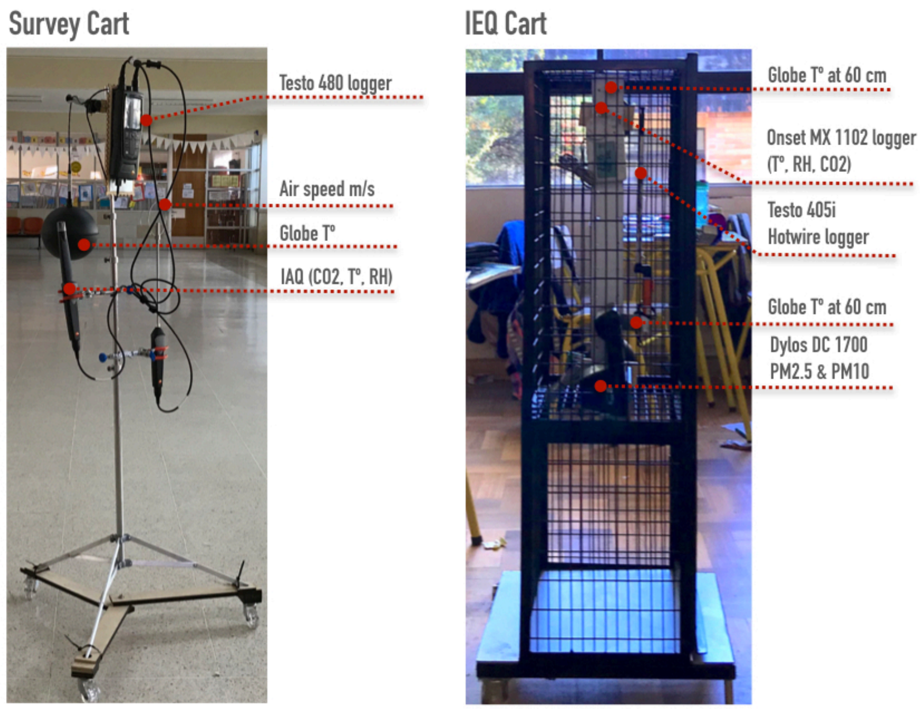


Figure 5.4. Indoor climate measurement equipment. Left survey cart, used for each classroom measured physical thermal conditions while collecting surveys responses. Right, IEQ cart left for the entire length of school day inside a selected classroom.

The operative temperature (T_{op}) was calculated as the average of the air temperature (Ta) and the mean radiant temperature (MRT), as specified in ASHRAE 55 (ASHRAE, 2017). The prevailing mean outdoor air temperatures ($T_{pma(out)}$) was derived using a 7-day exponentially-weighted average based on the studies of Humphreys (Humphreys & Nicol 1998; Humphreys and Nicol 2002; Humphreys, & Roaf 2012; Jungsoo & de Dear 2017) and ASHRAE 55 (ASHRAE, 2017), Equation (5.1). This method puts more weight on temperatures from more recent days, as noted by Nicol and Humphrey (Humphreys & Nicol, 1998), since people's responses depend heavily on their immediate thermal histories. As seen in Figure 5.6, indoor operative temperature plotted in ASHRAE 55-2017 adaptive chart, ranging from ~7.5 to ~11 ºC, falls outside the comfort zone. Only at the beginning of the study (April) were temperatures inside the comfort zone.

$$\overline{T_{pma(out)}} = (1-\alpha)[t_{e(d-1)} + \alpha\, t_{e(d-2)} + \alpha^2\, t_{e(d-3)} + \alpha^3\, t_{e(d-4)} + \ldots \quad (5.1)$$

where $t_{e(d-1)}$ is the daily mean outdoor temperature for the day before the day in question, and $t_{e(d-2), \ldots}$ daily mean outdoor temperature for the day before and so forth. $T_{pma(out)}$ is the exponentially weighted running mean of the outdoor temperature (ASHRAE, 2017). α is a constant between 0 and 1 that controls the senitivity of the running mean to changes in weather outdoor temperature. Recommended =0.8 (ASHRAE, 2017).

For this study, α was set to 0.8 (slow response) based on ASHRAE 55 and EN 15251, consistent with other studies on students (Teli et al., 2013; Haddad, Osmond, & King, 2016)

The predicted optimum comfort temperature (T_{comf}) was calculated for each classroom surveyed based on ASHRAE 55-2017 adaptive model equation (5.2).

$$T_{comf} = 0.31T_{pma(out)} + 17.8 \quad (5.2)$$

where T_{comf} is the optimal operative temperature for thermal comfort and $T_{pma(out)}$ represents the prevailing mean outdoor air temperature from a period of 7 to 30 consecutive days before the day in question (ASHRAE, 2017).

5.2.5. Questionnaire Design

Thermal comfort surveys have been designed and standardized for studying adults in office settings. Previous studies have shown difficulties associated with children's conceptual understanding of the questionnaires which were originally for adults (Teli, James & Jentshc 2012; Ter, Hensen, Loomans, & Boerstra, 2013). Modifications have been made in this study to target the student-age group based on previous studies (Trebilcock et al., 2016b; Teli et al., 2012; and Haddad, King, Osmond, & Heidari, 2012). Touch-sensitive tablet technology was incorporated for collecting the survey responses, differing from the traditional paper-based technique typically used in previous studies. A single survey question was designed to fit on the screen to avoid confusion. The survey also included the use of emoji images and colors for variouss scales, for easier, readable comprehension. Qualtrics software, version 2019 (Qualtrics, 2005), was used to collect responses. Use of these devices greatly aided in engaging the students in the activity, keenly raising interest and participation. The entire survey (all scales and questions) was conducted in Spanish. Before carrying out the actual surveys, pilot studies were conducted in order to ensure the proper functioning of tablets, to gather feedback on the clarity of the questions, and prepare for logical administration of the surveys. Multiple versions of the survey questionnaire were checked with an external assistant teacher and university professors to ensure that it was suitable for the age group.

The questionnaire was divided into five parts: 1) “right-here-right-now” type of questions on the current status of thermal comfort, air movement, and air quality using thermal sensation vote (TSV), air quality sensation vote (AQV), preference and acceptability (see Table 5.2 for reference). Section one also included clothing information regarding items worn during the time of the survey; 2) general personal satisfaction and perception about home and classroom environmental conditions, health-related symptoms experienced in the past; 3) house conditions; 4) personal perception of impacts of classroom environmental parameters on class work; and 5) general demographic information, gender, age, nationality, and anthropometrics of height and weight. For this paper, results from survey sections 1 and 5 are presented.

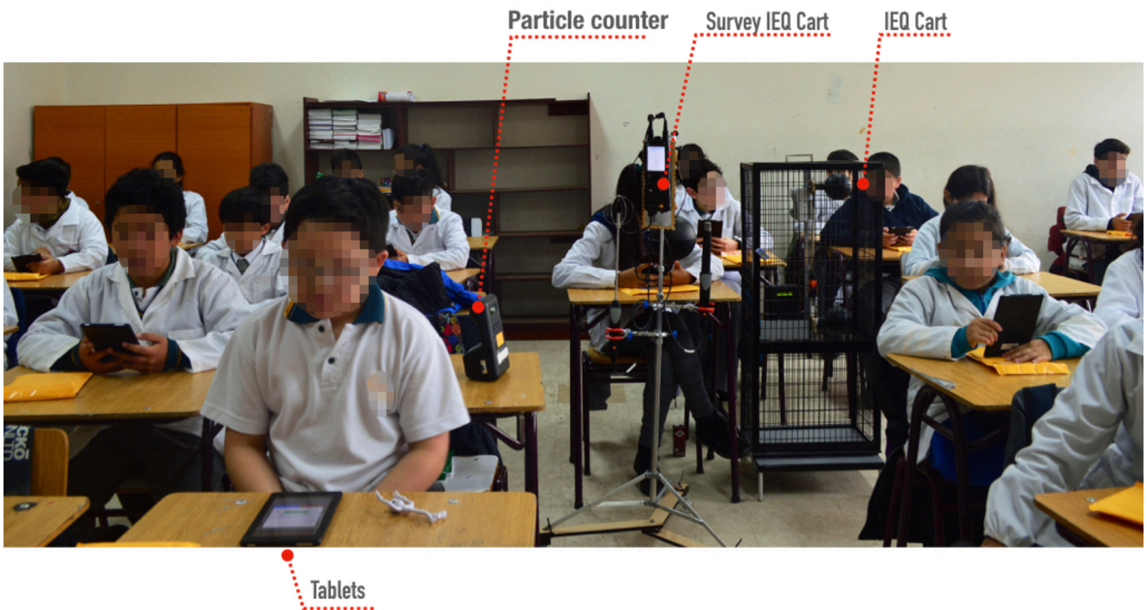


Figure 5.5. Fieldwork set-up and students responding to questionnaire on tablets

Surveys were administered 30 minutes after students and teachers had settled (i.e., sat still) in their classroom environments, to allow student metabolism to stabilize and eliminate the impact of metabolic rate on their thermal perception. This time frame has been adopted in previous studies and it has been considered as an appropriate margin (Kim & de Dear, 2018; Montazami, Gaterell, Nicol, Lumley, and Thoua, 2017; Trebilcock, Soto & Figueroa, 2014; Haddad, Osmond, King & Heidari, 2014; and Teli, Jentsch, James, 2012). Specific classroom times were selected for visits, to avoid periods when students had PE class on the day of the survey, to minimize higher metabolic activity levels. Measurements were collected during two classroom visits on the same day (morning 8:30–11:30 am and afternoon 1:00–4:30 pm respectively) during fall and winter season. The field study used a longitudinal survey approach: the same classrooms and students were surveyed in both seasons. Because of school academic schedules (ending of first semester and winter break) in June and July months, the study was conducted in four schools only during the winter season, instead of all nine studied in the first campaign. It is important to note that these four schools had the same participating subjects from the first field study during the fall, with minor changes due to newly registered students or students withdrawn from the school.

5.2.6. Personal Parameters: Assessing Clothing Insulation and Activity Level

In Chilean schools, students have a strict dress code, similar to other countries like Iran (Haddad, Osmond & King, 2019). They are required to wear their school uniforms, throughout all grade levels (i.e., up to 12^{th} grade level). School uniforms can vary among different types of schools, but in general there is a formal ensemble for girls and boys that is worn most of the time and a more relaxed ensemble for when they have physical education (P.E.)

Clothing ensemble insulation values for each individual student were estimated based on the checklists from ISO 7730 (ISO 7730, 2005) and ASHRAE 55 (ASHRAE, 2017) to match Clo levels of Chilean student uniforms and teacher outfits (reference appendix 1, 2, and 3). The metabolic rate for students who are mostly seated, writing or performing light work is classified as "nearly sedentary" and is equivalent to 1.2 met (70 W/m^2 or 22 $Btu/h{\cdot}ft^2$), according to ISO 7730 (ISO 7730, 2005). Haddad et al. (2014) measured values between 1.2 and 1.4 met for the same "nearly sedentary" metabolic state.

Table 5.2. Summary of questionnaire items, scales and numerical coding used in the analysis

Thermal Sensation Vote (TSV)		Thermal Preference (TP)		Thermal Acceptability (TA)		Air Movement Preference (AMP)		Air Quality Vote (AQV)	
How do you feel right now? ¿Cómo te sientes en este momento?		How would you prefer the temperature to be right now? ¿Cómo prefieres la temperatura en la sala de clases?		How do you perceive the temperature in this classroom right now? ¿Cómo percibes la temperatura en la sala de clases en este momento?		How would you prefer the air movement to be? ¿Cómo prefieres que sea el movimiento de aire en la sala de clases?		How do YOU find air quality right now in this classroom? ¿Cómo sientes tú la calidad del aire ahora en tu sala de clases?	
Mucho calor (+3)	Hot (+3)	Más Calurosa (3)	Warmer (3)	Inaceptable (1)	Unacceptable (1)	Más circulación de aire (3)	More air movement (3)	Muy Fresco (+3)	Very Fresh (+3)
Calor (+2)	Warm (+2)							Fresco Moderado (+2)	Moderately Fresh (+2)
Algo de Calor (+1)	Slightly warm (+1)							Un Poco Fresco (+1)	Slightly Fresh (+1)
Neutro (ni frío ni calor) (0)	Neutral (0)	Sin Cambio (2)	No Change (2)			Sin Cambio (2)	No Change (2)	Neutro (0)	Neutral (0)
Algo de Frío (-1)	Slightly cool (-1)							Un Poco Pesado (-1)	Slightly Stale (-1)
Frío (-2)	Cool (-2)							Pesado Moderado (-2)	Moderately Stale (-2)
Mucho Frío (-3)	Cold (-3)	Más Fría (1)	Cooler (1)	Aceptable (2)	Acceptable (2)	Menos circulación de aire (1)	Less air movement (1)	Muy Pesado (-3)	Very Stale (-3)

The thermal sensation votes were collected from students and teachers on an ASHRAE scale which included a range from -3 (Cold) to + 3(Hot) with +/-0.5 point marks in between. After data analysis, responses revealed very little votes on the 0.5 point marks. Therefore these were merged to prodruce a seven-point scale without intermediate values.

5.3. Results

5.3.1. Environmental Characteristics of Surveyed Classrooms

A descriptive statistical summary of indoor and outdoor environmental parameters of naturally ventilated classrooms for fall and winter season is listed in Table 5.3 and Table 5.4. Values include mean, standard deviation, and range by school type of total averages for all surveyed classrooms. Mean daily outdoor temperature (Ta(out)) and prevailing mean temperature (Tpma(out)) for each survey day were calculated. There are no noticeable differences between outdoor temperatures of the different types of schools, the mean daily outdoor temperature for fall ranged from 8.07 to 14.47ºC with a mean of 11.53ºC. The prevailing mean outdoor temperature ranged from 7.87ºC to 11.21ºC with a mean of 9.80 ºC, which is 1.73 degrees lower compared to the daily mean outdoor temperature. Based on the adaptive model prescribed by ASHRAE 55 (ASHRAE 55, 2017), averages of prevailing mean outdoor temperatures calculated fell below the limits permitted by the standard for Public and Private-nonsubsidized in Fall (i.e., permissible range of 10ºC to 33.5ºC).

It is important to note that at the beginning of the field study, in fall, high outdoor temperatures were measured (14ºC) and at the end of the fall fieldwork (8.0ºC). The total length of the fall campaign took about a month, starting April 23rd with school 1 and ending May 30th with school 9. During winter, there is a 3ºC noticeable difference between public and both types of private schools' prevailing mean outdoor temperatures. This temperature difference occurred because public school classrooms were surveyed at the beginning of winter, July 9th, just before students and teachers went into winter break. The daily mean outdoor temperature was 10.1ºC and the prevailing mean outdoor temperature was 9.2ºC. However, the remainder of the winter campaign surveys for both private-subsidized and nonsubsidized schools (i.e., S1 to S3) were collected from August 1st to August 3rd, which additionally coincided with a cold-wave with mean daily outdoor temperatures of 6.1ºC.

Table 5.3 Fieldwork physical measurements for fall

	$T_{a(out)}$(ºC)	$T_{pma(out)}$(ºC)	Tg (ºC)	Ta (ºC)	Rh (%)	Va (m/s)	CO_2 (ppm)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)
Public									
Mean	12.2	9.6	20.3	18.92	75.3	0.09	1732.2	38.8	123.0
SD	2.2	0.7	1.5	0.91	8.02	0.01	756.1	7.8	18.5
Min.	8.1	8.8	17.8	16.50	55.4	0.07	944.8	25.8	95.0
Max.	8.1	10.7	23.6	21.12	84.9	0.10	3330.4	52.6	154.8
Private-subsidized									
Mean	11.4	11.0	23.1	21.82	50.03	0.09	1347.5	28.7	89.3
SD	0.7	0.2	1.1	0.75	6.0	0.04	721.0	4.7	13.1
Min.	10.8	10.8	21.5	20.94	42.40	0.01	858.0	23.0	75.7
Max.	12.4	11.2	24.7	23.79	63.4	0.16	3275.3	37.3	115.7
Private-nonsubsidized									
Mean	10.6	9.3	20.6	20.12	61.3	0.09	1649.2	42.8	94.8
SD	1.1	1.2	1.7	1.41	6.0	0.01	576.9	8.2	13.9
Min.	9.4	7.9	17.4	17.42	47.4	0.07	909.4	31.7	74.4
Max.	12.2	10.7	23.8	22.33	71.6	0.11	3187.3	60.0	126.1
Total									
Mean	11.5	9.8	21.02	19.9	65.8	0.09	1625.2	38.4	105.0
SD	1.8	1.02	1.9	1.5	12.4	0.02	716.2	7.4	15.6
Min.	8.1	7.9	17.4	16.5	42.4	0.01	858.0	27.6	82.9
Max.	14.5	11.2	25.0	23.8	84.9	0.16	3330.4	52.5	135.5

$T_{a(out)}$ = Mean daily Outdoor Air Temperature (∘C)
$T_{pma(out)}$ = Prevailing mean outdoor air temperature (∘C), using a 7-day running mean exponential de
function
Tg = Indoor Globe Temperature (°C)
Ta = Indoor Air Temperature (°C)
Rhi = Indoor Relative Humidity (%)
Va = Indoor Air Velocity (m/s)
CO_2 = Indoor Carbon Dioxide (ppm)
$PM_{2.5}$ = Indoor Particulate Matter (≤ 2.5 µg/m^3)
PM_{10} = Indoor Particulate Matter (≤ 10.0 µg/m^3)

Table 5.4 Fieldwork physical measurements for winter

	$T_{a(out)}$ (ºC)	$T_{pma(out)}$ (ºC)	Tg (Cº)	Ta (Cº)	Rh (%)	Va (m/s)	CO_2 (ppm)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)
Public									
Mean	10.1	9.2	19.8	18.1	64.4	0.08	1960.0	38.8	123.0
*SD	-	-	1.8	1.6	2.6	0.01	737.1	7.8	18.5
*Min.	10.1	9.2	17.3	15.0	61.9	0.07	1075.2	25.8	95.0
*Max.	10.1	9.2	22.1	20.0	61.0	0.10	3174.4	52.6	154.8
Private-subsidized									
Mean	8.7	6.1	21.0	19.9	65.8	0.09	1625.2	28.7	89.3
SD	1.5	0.01	1.9	1.5	12.4	0.02	716.2	4.7	13.1
Min.	7.1	6.1	17.4	16.5	42.4	0.01	858.0	23.0	75.7
Max.	10.1	6.1	25.0	23.8	84.9	0.16	3330.4	37.3	115.7
Private-nonsubsidized									
Mean	7.4	6.1	16.8	16.9	62.4	0.09	2066.3	42.8	94.8
*SD	-	-	0.7	0.9	3.0	0.00	971.7	8.2	13.9
*Min.	7.4	6.1	15.6	15.3	58.2	0.09	1035.5	31.7	74.4
*Max.	7.4	6.1	17.5	17.8	66.5	0.10	3580.4	60.0	126.1
Total									
Mean	8.7	6.8	19.4	18.8	62.7	0.09	1914.9	38.4	105.0
SD	1.5	1.3	2.6	2.1	6.2	0.02	877.7	7.4	15.6
Min.	7.1	6.1	14.5	15.0	42.6	0.05	1035.5	27.6	82.9
Max.	10.1	9.2	24.0	23.8	69.6	0.13	4326.5	52.5	135.5

** Only one school was surveyed in one day in this season, therefore, the is only one value for averages outdoor temperatures, same value for min., and max., and now standard deviations.*

$T_{a(out)}$ = Mean daily Outdoor Air Temperature (ºC)
$T_{pma(out)}$ = Prevailing mean outdoor air temperature (ºC), using a 7-day running mean exponential decay function
Tg = Indoor Globe Temperature (ºC)
Ta = Indoor Air Temperature (ºC)
Rhi = Indoor Relative Humidity (%)
Va = Indoor Air Velocity (m/s)
CO_2 = Indoor Carbon Dioxide (ppm)
$PM_{2.5}$ = Indoor Particulate Matter (≤ 2.5 µg/m^3)
PM_{10} = Indoor Particulate Matter (≤ 10.0 µg/m^3)

The indoor operative temperatures (T_{op}) for the fall study fell within the range of 17.4–24ºC, with a mean value of 20.7ºC. In winter, the range of indoor operative temperatures was 14.9–24.0ºC, with a mean value of 19.3ºC. Shown in Table 5.5 and Table 5.6, the operative temperature calculated for five of nine schools in the fall season fell outside the adaptive comfort zone of standard ASHRAE 55 (as seen in Figure 5.6), due to prevailing mean outdoor temperatures <10ºC, and in winter all of the operative temperatures fell below the comfort zone. Air velocity (V_a) in all classrooms during all visits was very low, almost imperceptible, with a negligible mean speed of 0.09 m/s in fall and winter (reference Table 5.3 and Table 5.4), which had a marginal effect on subjects' thermal sensation. Maximum values ranged from 0.13–0.16 m/s. Indoor relative humidity (RH) in fall ranged from 42% to 85%, with an average of 66%. Public schools registered the highest mean RH of 75.3% with a standard deviation of 8.0 in fall season; in comparison, other schools had mean values of 61% and 50%. However, during winter, RH across all schools was very similar, in the 62–66% range. A maximum RH value was measured in private-subsidized schools of 85%, also reference Figure 5.7.

Table 5.5. Mean values of outdoor and indoor temperature and thermal sensation vote of students in each school in fall season

School ID	*N*	*$T_{pma(out)}$(ºC)*	*T_{op}(ºC)*	*(TSV)* Mean	*(TSV)* Std. Deviation	*(AQV)* Mean	*(AQV)* Std. Deviation
S1	121	11.2	22.6	0.6	0.9	-0.2	1.3
S2	211	10.8	22.8	0.3	1.0	-0.6	1.4
S3	102	10.2	21.6	0.2	1.0	-0.01	1.3
S4	168	9.2	20.7	-0.1	1.2	0.1	1.4
S5	166	10.7	19.7	0.2	1.1	0.3	1.3
S6	188	10.0	21.3	-0.02	0.8	-0.1	1.4
S7	284	9.4	20.1	0.1	1.1	-0.1	1.3
S8	158	7.9	18.8	-0.1	0.9	0.1	1.2
S9	144	9.1	19.0	-0.4	1.4	-0.3	1.5

N = number of survey responses
$T_{pma(out)}$ = Prevailing mean outdoor air temperature (ºC), using a 7-day running mean exponential decay
T_{op} = Indoor Operative Temperature (ºC)
TSV = Thermal Sensation Vote
AQV = Air Quality Perception Vote
Green represents public schools, yellow private-subsidized, and blue private-nonsubsidized.

Table 5.6. Mean values of outdoor and indoor temperature and thermal sensation vote of students in each school in winter season

School ID	*N*	$T_{pma(out)}$ (ºC)	T_{op} (ºC)	*(TSV)*		*(AQV)*	
				Mean	*Std. Deviation*	*Mean*	*Std. Deviation*
S1	203	6.1	19.2	-0.2	1.1	0.1	1.2
S2	189	6.1	20.9	0.5	1.03	-1.0	1.3
S3	109	6.1	16.8	-0.7	1.3	0.2	1.3
S5	141	9.2	19.3	0.02	1.4	0.1	1.4

N = number of survey responses
$T_{pma(out)}$ = Prevailing mean outdoor air temperature (ºC), using a 7-day running mean exponential decay
T_{op} = Indoor Operative Temperature (ºC)
TSV = Thermal Sensation Vote
AQV = Air Quality Perception Vote
Green represents public schools, yellow private-subsidized, and blue private-nonsubsidized.

Classroom indoor mean air temperature (T_a) was 19.9ºC, with a range of 16.5–23.8ºC in fall season. In winter mean air temperature was 18.8ºC, with a range of 15.0–23.8ºC. Public schools had the lowest mean air temperatures in fall but private-nonsubsidized in winter, but differences are not significant.

High concentrations of CO_2 were recorded across all schools in both campaigns, ranging from 858 to 3330 ppm with a mean of 1625 ppm during fall and 1036 to 4327 ppm, with a mean 1915 ppm in winter. Public school had the highest concentrations in fall with a range of 945 to 3330 ppm and a mean of 1732 ppm with a standard deviation 756 ppm. However, private-nonsubsidized schools registered the highest values with a mean of 2066 ppm and a range of 1036 to 3580 ppm.

Particulate matter concentrations, $PM_{2.5}$ during fall ranged from 27.6 to 52.5 µg/m^3 with an average of 38.4 µg/m^3, and in winter values ranged from 48.4 to 52.1 µg/m^3, and an average of 56.0 µg/m^3. Additionally, PM_{10} was also measured in all classroom visits, ranging from 82.9 to 135.5 μg/m^3 in fall with an average of 105.0 μg/m^3. For winter the range was of 103.4 to 107.7 μg/m^3 and average of 177.0 μg/m^3.

Public schools in fall had the highest concentration for $PM_{2.5}$ of and PM_{10} compared to the rest of the schools, however, in the winter the public-subsidized had the highest concentrations for both sizes of particulate matter.

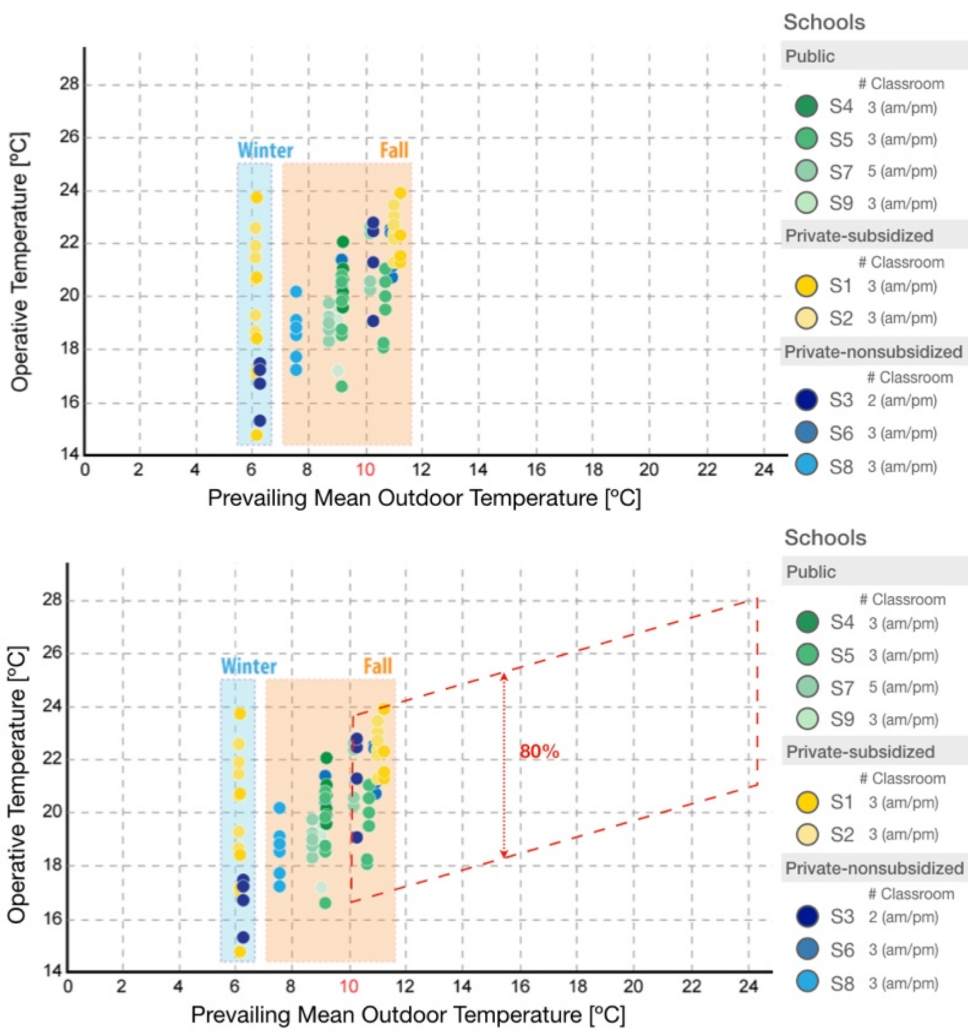


Figure 5.6. Indoor operative temperatures with prevailing mean outdoor temperatures for fall and winter in all classrooms. Each point represents an individual survey (taken twice a day am and pm) in each classroom. The bottom figure shows the projected ASHRAE-55 adaptive comfort zone over the measurements. Only 50% of the calculated operative temperature for each classroom visits fall inside the comfort zone; the rest are outside. In winter all the operative temperature are outside and below the 10ºC.

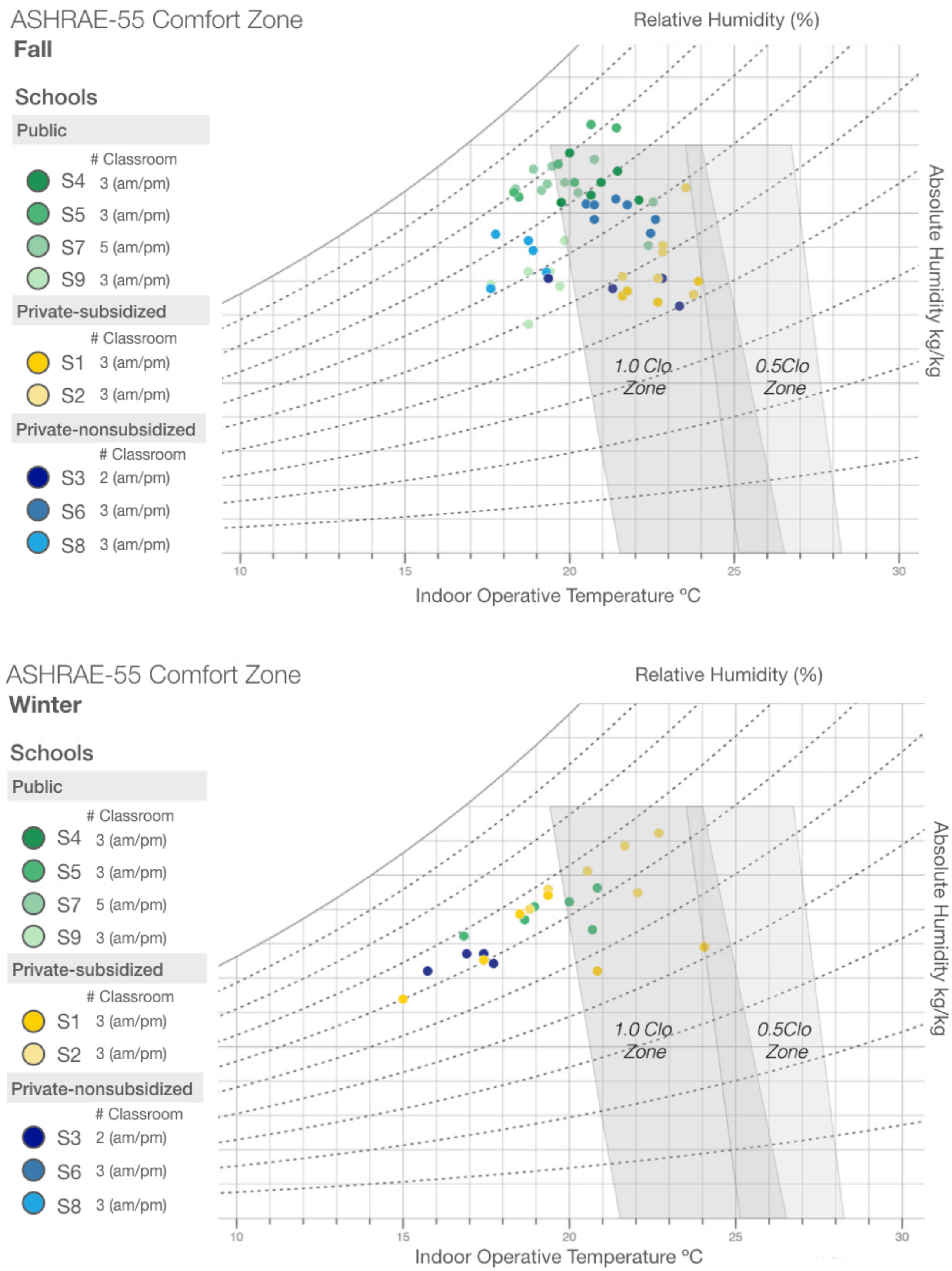


Figure 5.7. ASHRAE–55 psychrometric chart with comfort zone for 1 Clo and 0.50 Clo. Measured indoor operative temperature and relative humidity during fall (top) and winter (bottom), each point represents an individual survey (taken twice a day am and pm) in each classroom. It can be seen that public schools had the highest RH values compared to both private schools types.

5.3.2. Personal Parameters

The clo values for the different sets of ensembles (formal or relaxed sports uniform) ranged from 0.62 to 1.24. Clothing insulation estimates were close to those assumed by ASHRAE (ASHRAE 55, 2017) for typical indoor clothing of 0.5 for summer and 1.0 winter. However, many teachers and students wore parkas or insulated jackets inside the classrooms, so clo values reached as high as 1.66 to 1.86, as seen in Figure 5.8. Therefore, clo insulation values in primary schools in Chile are substantially higher than those recommended by ASHRAE 55. Students' clo in fall had a mean of 0.95 clo and in winter of 1.05 clo; for teachers, a mean of 0.93 clo in fall and 1.24 in winter.

The metabolic rate, for students and teachers, was observed to be near 1.2 met, since adjustments were taken during the surveys in which students and teachers were mostly seated, writing or doing light work, for a least 30 minutes prior to the survey.

Figure 5.8 School uniforms across different types of schools. Cloth mean values were 0.95 clo in Fall, and 1.24 clo in Winter based on the responses collected from the surveys. However, when children wore jackets, clo values could range from 1.66 to 1.84, depending on insulation layers.

5.3.3. Subjective Assessment of Indoor Thermal and Air Quality Environment

A statistical summary of student perceptions of thermal and indoor air quality environment is shown in Table 5.5 for fall and Table 5.6 winter.

Figure 5.9 shows the distribution of thermal sensation votes (TSV) for students and teachers for all the schools during both seasons. The votes fell symmetrically (normal distributions) within the three central categories of the scale: slightly cool, neutral, and slightly warm [-1, 0, +1]. The average mean vote on the thermal sensation scale for students was 0.14 ±1.17 in fall and -0.11 ±1.28 for winter. Mean vote for teachers 0.03±1.05 in fall and winter -0.32 ±1.41. The uncertainty quoted correspond to 1 standard deviation. A total of 42% of the students and teachers expressed their thermal sensation as "neutral" in fall. In winter 36% of students voted on neutral and a symmetrical 21% for slightly cool and slightly warm. For teachers in winter, 28% voted on neutral but with a tendency towards the cold side of the scale with 44% of the votes versus 28% on the warm side.

The central three categories (-1, 0, +1) of the seven-point scale, and based on PPD thermal comfort index (Fanger, 1970), are deemed the acceptable range for people to feel comfortable with their thermal environment. The extreme categories of thermal sensation scale on the cold (-3, -2) and warm (+3, +2) sides are considered to express dissatisfaction. ASHRAE 55 (ASHRAE 55, 2017) recommends a minimum of 80% acceptability for comfort. For this study, the surveyed classrooms in fall, 82% of students and 85% of the teachers were within the middle range of the thermal sensation scale; in the winter, 78% of

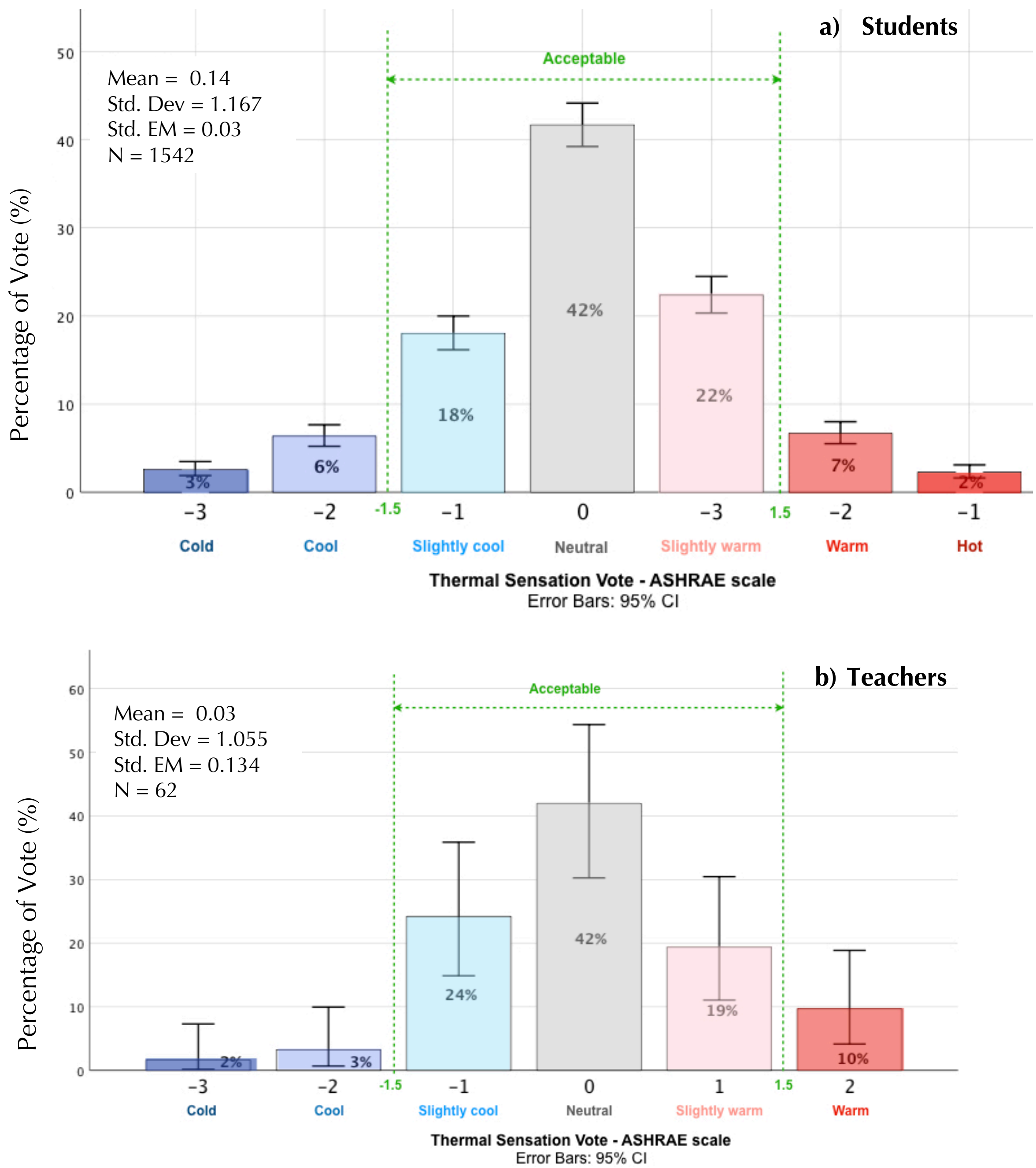


Figure 5.9. Distribution of thermal sensation votes for all students (a) and teachers (b) across all schools. Votes fall within the three central categories of the scale: slightly cool, neutral, and slightly warm (acceptable range based on ASHRAE-55), 82% for students and 78% for teachers. Acceptable is the percentage satisfied occupants using ASHRAE TSV 7-point scale is within = -1.5 ≤ acceptable ≤ +1.5 (when using a scale resolution of 0.5). For the study, surveys included a scale resolution of 0.5, but after analysis, these values were combined into integers. Std. Dev = standard deviation, Std. EM = standard error of the mean.

the students and 64% of the teachers were within the range. These results indicate general perceptions exceeded or were close to the 80% acceptability criterion. A decrease in the acceptability percentage for teachers in winter is consistent with the cold outdoor temperatures, and their thermal sensation votes are lower than those of children.

Figure 5.10 shows boxplots of TSV distribution for students and teachers across all nine schools, for the fall season. Votes are also centered in the middle three categories (-1, 0, +1). Students votes show a broader spread in comparison with teachers, particularly in public schools, with greater variance outside the acceptable ranges more evident towards the middle/end of the fieldwork, corresponding to lower outdoor temperatures.

Distribution of the votes moves towards the colder side of the scale for both students and teachers. By looking at the distribution of TSV across all different classrooms in the four public schools Figure 5.11, the median votes are centered in the neutral part of the seven-point scale, and the spreads of 25% and 75% quartiles fell within the three central categories. However, as seen in Figure 5.11wider spreads of minimum and maximum of the scale occurred in school 7 and 9, which corresponds towards the end of the fall season, and prevailing mean outdoor temperatures were lower with respect to the beginning of the campaign. This suggests that TSV for students can be influenced by outdoor weather or other factors (i.e., gender), besides indoor classroom temperatures. School 9, e.g., is a primary school of only girls, unlike the rest.

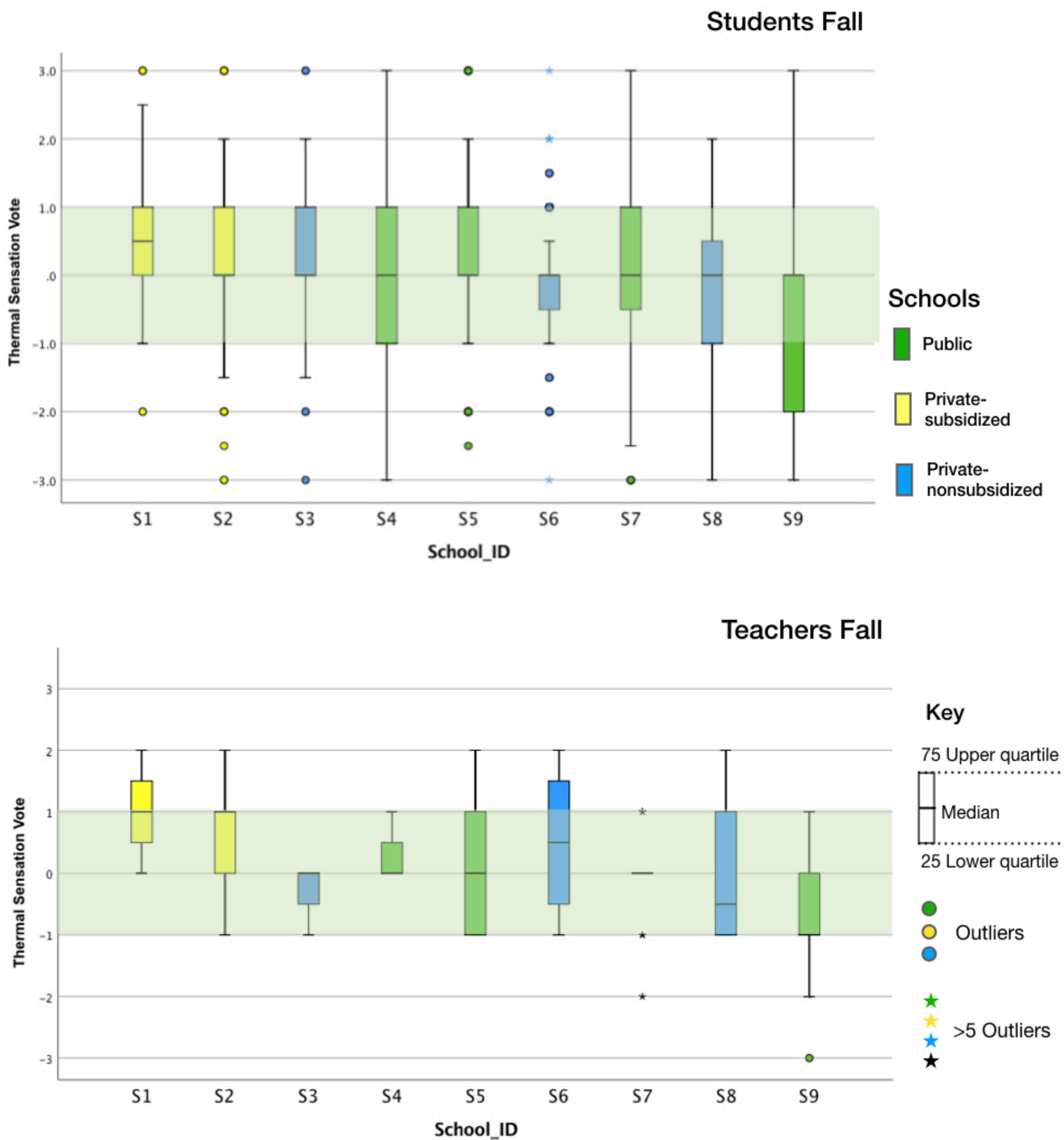


Figure 5.10. Thermal Sensation Votes of students (top) and teacher (bottom) per school type during fall season. Greater variance of the votes is seen in students compared to teachers. In general TSV fall within the three central categories across all schools.

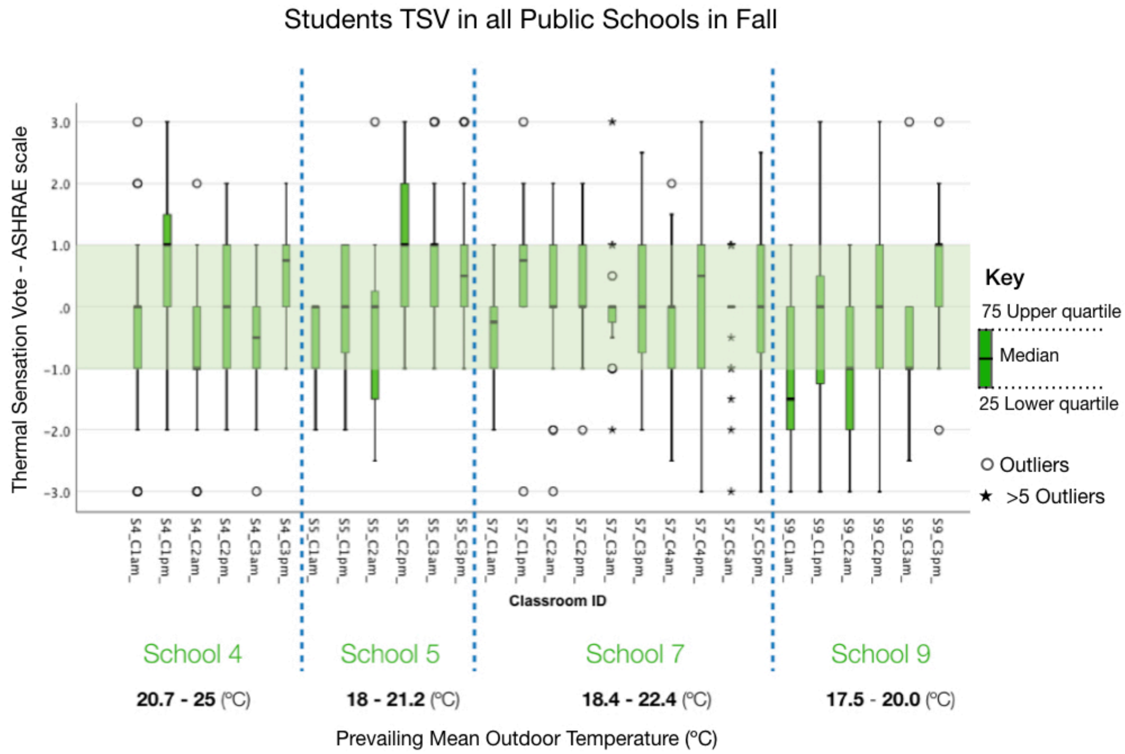


Figure 5.11. Student thermal sensation across different classrooms and in all public schools during fall surveys. Each bar represents an individual sampling obtained either in the morning or afternoon. As the outdoor temperature dropped, TSV moved to the colder side of the scale. Also, an increase in variance happens towards the end of the fieldwork.

A one-way ANOVA was used to compare the TSV for the three groups of students. A statistically significant difference was measured ($F(2,1339) = 20.95$, $p = .001$). To determine where the difference occurred between various schools, a post hoc test using Bonferroni correction (i.e., to keep the Type I error at 5% overall) was run and revealed that a statistically significant difference existed between the perceptions of students in public and private-subsidized by a mean difference of -0.46 TSV ($p<0.001$). Also, a statistically significant difference between Private-nonsubsidized and private-subsidized by a mean difference of -0.464 TSV ($p<0.001$). There was no statistically significant difference between public schools and private-nonsubsidized, mean difference of -0.01 TSV ($p>1.0$). Additionally, one-way ANOVA was run to compare the mean TSVs among teachers across school types in fall. No statistically significant difference was reported, ($F(2,59) = 3.01$, $p = .057$).

Figure 5.12 shows the crosstabulation between TSV in relation to their Thermal Preference Vote (TPV) across a three-point scale suggested by McIntyre, for students in fall. It can be seen that as the thermal sensation increases (i.e., from cold to hot), percentage students of votes increase for wanting “cooler” temperatures. On the other hand, as thermal sensation increases towards the cooler side, votes increase for “warmer” temperatures. The distribution seems almost symmetrical. However, inconsistent responses occurred towards the warm side; for example, 37% of the students who felt hot (thermal sensation of +3) prefer warmer temperatures. This suggests that students might not have fully understood right-here right-now phrase. However, the total percentage of inconsistent votes only represents 3.9% (13 votes) as seen in Table 5.7 from the total number of votes (1542), a minimal percentage, demonstrating that the majority of the students did indeed understand the questionnaire and what was asked.

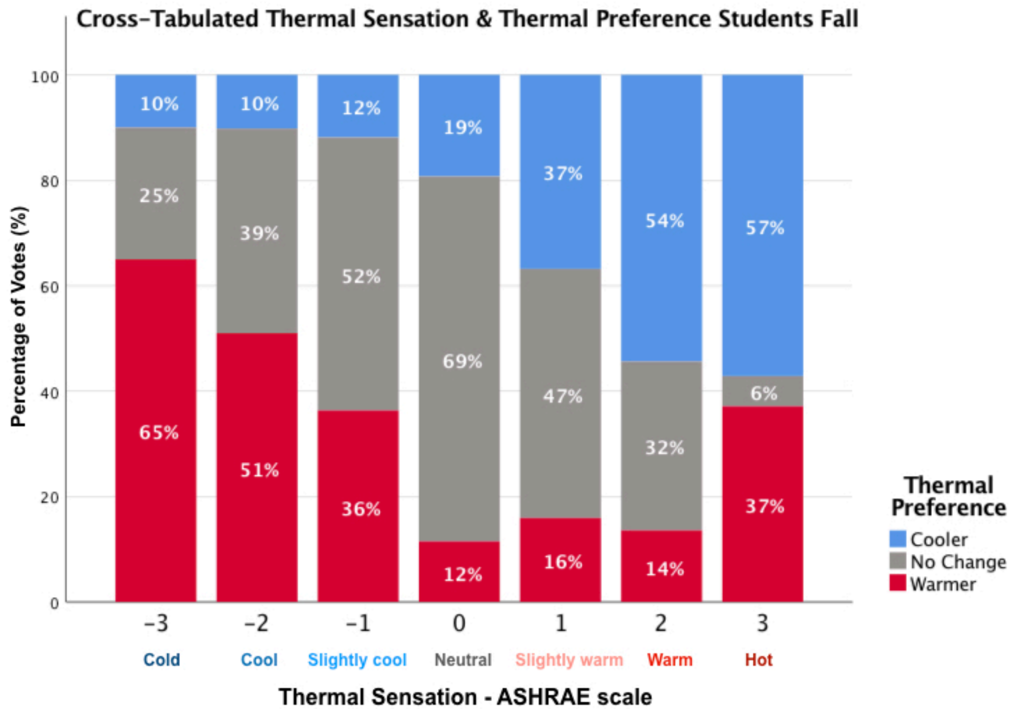


Figure 5.12. Cross-tabulation between thermal sensation (ASHRAE) and thermal preference votes of students in fall season. As move towards the warmer side of scale, the preference for cooler temperature increases. In other hand, as students votes move towards de cold side of the scale, thermal preference for warmer temperatures increases.

Table 5.7 Cross-tabulation between thermal sensation (ASHRAE) and thermal preference

	Thermal Sensation Votes (TSV)							
Thermal Preference	**-3**	**-2**	**-1**	**0**	**+1**	**+2**	**+3**	**Total**
Cooler (1)	4 (1.1%)	10 (2.7%)	33 (8.8%)	124 (33.2%)	127 (34.0%)	56 (15.0%)	20 (5.3%)	374 (100.%)
No Change (2)	10 (1.2%)	38 (4.6%)	144 (17.2%)	445(53.3%)	163(19.5%)	33 (4.0%)	2 (0.2%)	835 (100.%)
Warmer (3)	26 (7.8%)	50 (15.0%)	101 (30.3%)	74 (22.2%)	55 (16.5%)	14 (4.2%)	13 (3.9%)	333 (100.%)
Total	**40 (2.6%)**	**98 (6.4%)**	**278 (18.0%)**	**643 (41.7%)**	**345 (22.4%)**	**103 (6.7%)**	**35 (2.3%)**	**1542 (100%)**

Cross-tabulation between thermal sensation (ASHRAE) and thermal preference, n = number of votes (percentage with respect to number of votes)

Another way of looking at this relation of votes in the data is the question of "neutral" thermal state. Studies have suggested (Kwok & Chun, 2003, Wong & Khoo, 2003) that this is not always the preferred option. Table 5.8 crosstabulation grouped the central three categories of thermal sensation and extreme ends of dissatisfaction [-3, -2 & +2, +3]. Of the students that voted within the three main categories, 48.8% prefer no change in the temperatures of their classroom. However, those that felt slightly cooler, 18.3% voted to want cooler temperatures and in the slightly warmer scale, 14.9% prefer warmer temperatures, corroborating previous studies.

Table 5.8. *Cross-tabulation between thermal sensation (ASHRAE) and thermal preference*

	Thermal Sensation Votes (TSV)			
Thermal Preference	**(-3, -2)**	**(-1, 0, +1)**	**(+2, +3)**	**Total**
Cooler (1)	14 (0.9%)	284 (18.3%)	76 (4.9%)	374 (24.1%)
No Change (2)	48 (3.1%)	752 (48.8%)	35 (2.2%)	835 (54.1%)
Warmer (3)	76 (4.9%)	230 (14.9%)	27 (1.7%)	333 (21.5%)
Total	138 (8.9%)	1266 (83%)	138 (8.8%)	1542 (100%)

Cross-tabulation between thermal sensation (ASHRAE) and thermal preference, n = number of votes (percentage with respect to number of votes)

The survey also asked subjects about their preference of air movement and the air quality sensation vote (AQV) of their classroom. Figure 5.13 shows the distribution of votes from the question How do you find Air Quality right now in this classroom? in a seven-point scale based on a previous study (Kwok, 1997) for students and teachers in the fall season. Votes fell within the three central categories of the scale: slightly stale, neutral, and slightly fresh [-1, 0, +1], with very small differences around them as seen by the 95% confidence interval error bars. A small tendency can be seen towards the slightly stale side of the scale, a total of 28% of the votes for students versus 39% for teachers, suggesting that teachers are a bit more sensitive at perceiving the air quality of the classroom than students. The average mean AQV for students is -0.121 (SD = 1.42) and -0.18 (SD = 1.45) for teachers.

Figure 5.14 shows the crosstabulation between AQV in relation to their Air Movement Preference Vote (AMP) a three-point scale (more air movement, no change, and less air movement) similar to McIntyre thermal preference, for students in fall. Note that as air quality is perceived to be more stale (i.e., from neutral to very stale), the percentage of student votes increased towards “more air movement.”

On the other hand, as the air quality votes increase towards the fresh side of the scale (i.e., from neutral to very fresh), votes are very divided between wanting more air movement or no change. Inconsistent responses occurred towards the fresh side of the scale, for example, 57% of the students who felt the air was fresh (air quality vote of +3) preferred more air movement, suggesting that air movement is a preferred condition for children in their classroom environment. However, this sample only represents 1.6% (24 votes) from the total number of votes.

This result can also be evidenced in Table 5.9, a crosstabulation that looks at the relation between air quality sensation vote and air movement preference vote, by grouping the three central categories and extreme ends [-3, -2 & +2, +3]. The left side of the scale assumes votes of dissatisfaction of the air quality sensation. Of the students that voted within the three central categories, 40.5% prefer more air movement, 25% no change and 5.6 less air movement.

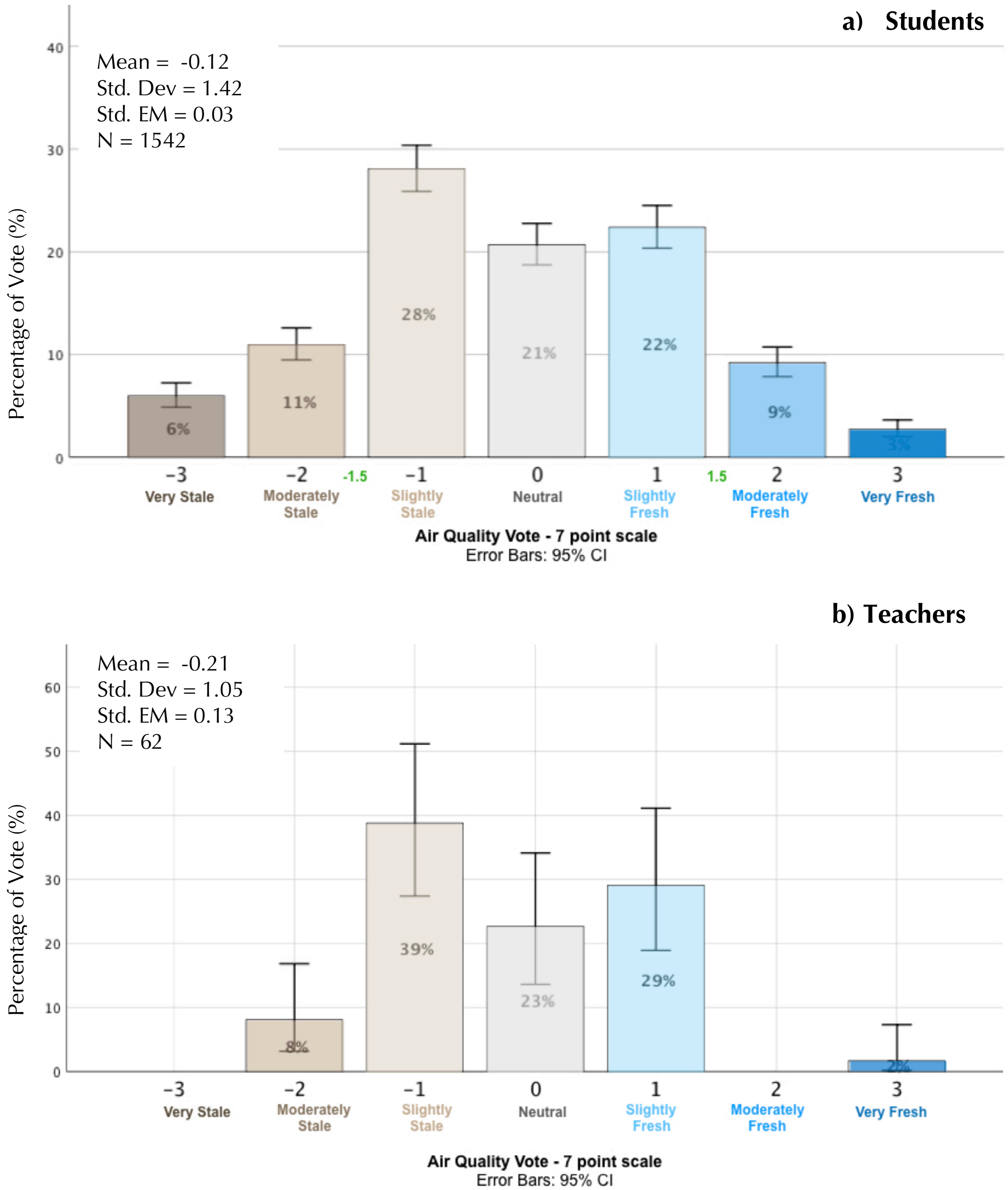


Figure 5.13. Distribution of Air Quality Perception Votes for students (a) and teachers (b) in the fall season. 75% of the votes for children fall within the central three categories of the scale, with 28% on slightly stale. For teachers, 91% of the votes are within the three central categories. The distribution of students votes is slightly skewed towards the more stale side of the scale, in comparison with teacher votes, 47% of the votes was towards the slightly stale to moderately stale.

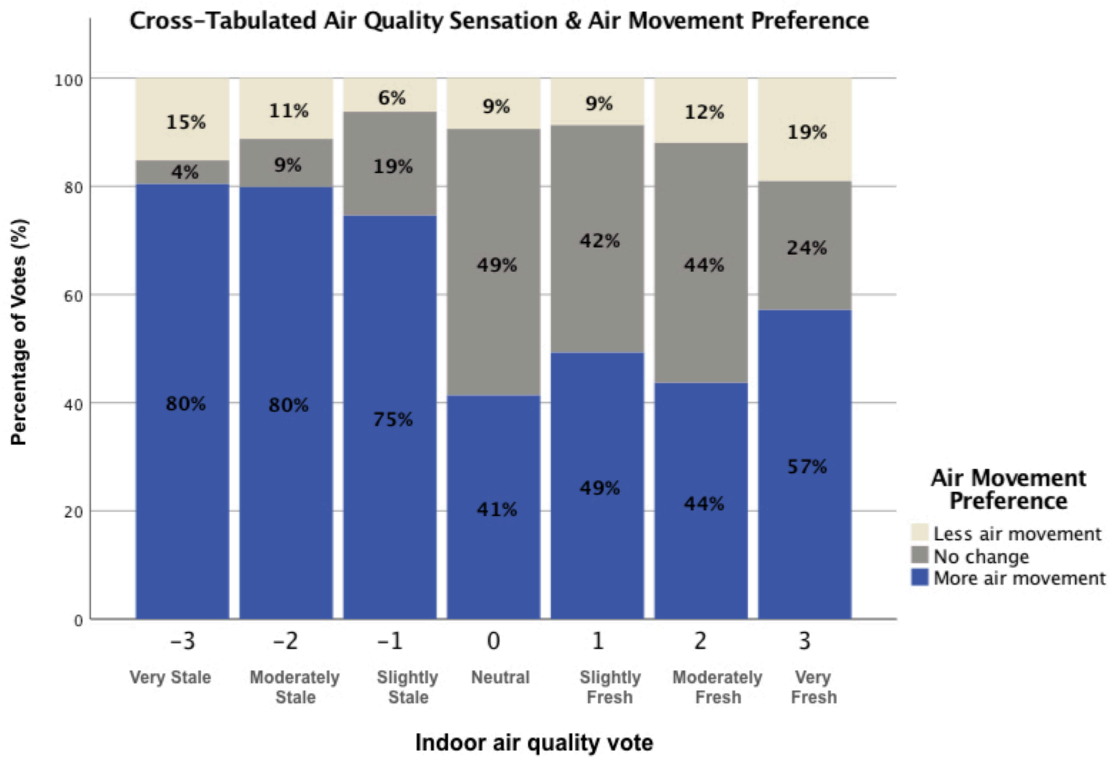


Figure 5.14. Crosstabulation of the relationship between Air quality sensation vote (AQV) and Air Movement Preference Vote (AMP) for students during fall surveys. Higher preference vote for more air movement is observed at stale conditions. However, students' prefer more air movement even at very fresh perceived conditions. In general, this confirms that students prefer more air movement in their classroom, consistent with the low air velocities measured in the classroom.

Table 5.9. Cross-tabulation of number of votes and their percentages between air quality sensation and air movement preference

	Air quality sensation vote (AQV)			
Air Movement Preference	**(-3, -2)**	**(-1, 0, +1)**	**(+2, +3)**	**Total**
Less air movement (1)	33 (2.1%)	87 (5.6%)	25 (1.6%)	145 (9.4%)
No Change (2)	19 (1.3%)	385 (25%)	73 (4.7%)	477 (30.9%)
More air movement (3)	209 (13.6%)	625 (40.5%)	86 (5.6%)	920 (59.7%)
Total	**261 (17%)**	**1097 (71.2%)**	**184 (11.9%)**	**1542 (100%)**

Cross-tabulation between air quality sensation and air movement preference, n = number of votes (percentage with respect to number of votes)

A Pearson Correlation analysis was performed between subjective votes and physical measurements as seen in Table 5.10. Subjects air movement preference votes with CO_2 concentrations shows a weak, negative correlation of r = -0.006, n= 1542, p= 0.800 as seen in Table 5.10.

5.4. Discussion

Participating subjects included middle school students and teachers. Overall, primary school children, aged 10–14, were capable of understanding thermal sensation and preference rating scales, and their responses are similar to responses from teachers. This is further supported by the fact that there were very few conflicted discrepancies when looking at TSV and TPV. Despite very cold classroom conditions, classroom occupants found those conditions comfortable, as oppose to those specified in ASHRAE-55.

Votes for TSV and TPV were found to be similarly related to environmental conditions, as seen in Table 5.9. This suggests that the environmental variables are effective indicators of students' thermal response. A negative correlation (r(1542) = -0.322, p=0.01) was identified between TSV and TPV during fall from student surveys. However, there were discrepancies between children's responses, such as feeling warm and wanting warmer temperatures.

Evaluating the air quality perceptions, students voted within the three central categories of the scale: slightly stale, neutral, and slightly fresh. Teacher votes were skewed towards the slightly stale conditions, suggesting they were a bit more sensitive at perceiving classroom conditions than students. This might be explained by the fact that

Table 5.10 Pearson correlation matrix, between physical measurements and subjective perceptions, with their significance

	Correlations	Subjective Perceptions Votes				Personal Parameter			Indoor environmental variables							
		TA	TPV	AMP	AQV	Clo	Age	Gender	Tpma(out) °C	Ta(out) °C	Tg °C	Ta (°C)	Rhi (%)	Va (m/s)	CO2 (ppm)	Top (°C)
Subjective Perceptions Votes	Thermal Sensation Vote	-0.004	-.322**	.180**	-.102**	-.107**	-.083**	.080**	.179**	.123**	.233**	.266**	-.115**	0.023	-.132**	.254**
		0.871	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.365	0.000	0.000
	Thermal Acceptability (TA)	1	0.011	-0.007	.254**	-0.032	-.080**	.093**	-0.006	0.018	0.031	0.046	0.004	0.042	0.024	0.037
			0.674	0.770	0.000	0.205	0.002	0.000	0.804	0.483	0.221	0.072	0.869	0.098	0.353	0.149
	Thermal Preference Vote		1	-.242**	.198**	.074**	0.049	0.000	-.079**	-0.005	-.166**	-.202**	.134**	-0.031	.050*	-.183**
				0.000	0.000	0.004	0.056	0.994	0.002	0.833	0.000	0.000	0.000	0.221	0.049	0.000
	Air Movement Preference			1	-.193**	-0.019	0.022	-0.010	0.042	-0.049	.112**	.141**	-.123**	0.024	-0.006	.125**
					0.000	0.455	0.395	0.707	0.102	0.055	0.000	0.000	0.000	0.351	0.800	0.000
	Indoor Air Quality Vote				1	-0.014	-0.043	.107**	-0.045	.103**	-.076**	-.109**	.105**	.052*	-0.010	-.087**
						0.579	0.088	0.000	0.078	0.000	0.003	0.000	0.000	0.039	0.708	0.001
Personal Parameter	Cloth insulation (Clo)					1	-0.007	-.215**	0.041	.111**	-.055*	-.134**	.147**	-0.009	.064*	-.077**
							0.777	0.000	0.111	0.000	0.031	0.000	0.000	0.725	0.011	0.002
	Age (yrs)						1	-0.005	-.092**	-0.017	-.155**	-.102**	-0.005	0.019	-.100**	-.149**
								0.836	0.000	0.504	0.000	0.000	0.835	0.463	0.000	0.000
	Gender (male/female)							1	0.047	.153**	.100**	.061*	0.035	0.045	0.036	.098**
									0.067	0.000	0.000	0.016	0.167	0.077	0.163	0.000
Indoor environmental variables	Prevailing mean outdoor Temperature Tpma(out)								1	.434**	.628**	.626**	-.357**	.069**	-.241**	.665**
										0.000	0.000	0.000	0.000	0.007	0.000	0.000
	Mean daily Outdoor Air Temperature Ta(out)									1	.139**	.122**	.467**	.074**	-0.043	.147**
											0.000	0.000	0.000	0.003	0.094	0.000
	Indoor Globe Temperature (Tg)										1	.692**	-.491**	-0.019	-.159**	.984**
												0.000	0.000	0.463	0.000	0.000
	Indoor Air Temperature (Ta)											1	-.595**	.070**	-.205**	.806**
													0.000	0.006	0.000	0.000
	Indoor Relative Humidity												1	-.143**	.452**	-.544**
														0.000	0.000	0.000
	Indoor Air Velocity (Va)													1	-.056*	0.029
															0.029	0.255
	Indoor Carbon Dioxide														1	-.181**
																0.000

Correlation coefficient range
0.51 to 1.0
0.31 to 0.5
0.1 to 0.3
0.0
–0.1 to 0.3
–0.31 to 0.5
–0.51 to 1.0

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
Top = Pearson Correlation

Bottom = Sig (2-tailed)

students are longtime residents to their classroom, spending most of their day in the same classroom while teachers moved to different classrooms throughout the day. The preference for more air movement was across all school types, even for the votes falling on the fresh side of the scale.

While collecting the different surveys, the author experienced very stale/stuffy classroom environments in all school types and attributed this to high levels of CO_2, PM_{10}, and $PM_{2.5}$. Even though student votes for indoor air quality might not be as effective in the "right-here-right-now" type of questions in the survey itself, their overall perception when asked in focus group interviews described deplorable air conditions.

Indoor air quality in all classrooms had high levels of CO_2 (>4,000), PM_{10} (>135), and $PM_{2.5.}$ (>50). Some of the factors that might explain these conditions: a) high density of occupants in the classrooms; b) little air movement which limited air ventilation rates (i.e., windows were mostly closed due to low outdoor temperatures); c) predominantly wood-burning for heat during the winter in these localities. A medium positive correlation was identified between CO2 and RH, $r(1542) = 0.467$, $p=0.01$. Students reported feeling tired and have difficulty concentrating. Also, the relative humidity was high (e.g., ranging from 60% to 75%) in all school types, presence of mold in walls and ceilings, as well as condensation in walls and windows were observed in classrooms visits. In some cases, mold can have a more significant impact on health and well-being of students and teachers (Philomena M Bluyssen, 2012; Chatzidiakou et al., 2012; Daisey, Angell, & Apte, 2003b), thus suggesting new strategies need to be implemented through better architectural design, that can improve indoor classroom conditions.

5.5. Conclusions

Student and teachers votes fall within the comfortable ranges of acceptability of ASHRAE-7 point scale, as seen in the normal distributions of thermal sensation with higher votes concentrated in neutral and thermal preference votes in no change, despite very cold conditions when compared to international standards. Students and teachers utilized adaptive mechanisms such as adding clothing such as scarfs, parkas, coats, mittens, and other pieces of clothing. Additionally, students during break times, increasing metabolic activity, shivering, huddling, and bringing in hot drinks to their classroom.

Classroom environmental parameters, such as humidity is negatively correlated with indoor temperature ($r = -0.595$, $p = 0.001$) and positively correlated CO_2 concentrations ($r = 0.452$, $p = 0.001$). Prevailing mean outdoor temperature is positively correlated with indoor air temperature ($r = 0.626$, $p = 0.001$).

Indoor air quality conditions are very deficient by ASHRAE-62.1. The latter can be explained by low ventilation rates (airspeed average of 0.09m/s in all school) due to little use of windows (because of outside noises, and cold outdoor temperatures), and crowded classrooms. Additionally, high concentration (by guidelines of WHO 2010, and ASHRAE-62.1) of particulate matter is due to dust, soil that children bring from the outside, windows located close to outside traffic streets, and high concentrations of fine particle PM2.5 due to domestic heating systems (i.e., wood-burning heaters).

Subjects indoor air quality perceptions (AQV) and thermal preference vote (TPV) have a median positively correlation, $r = 0.198$, $p = 0.001$, suggesting that the perceptions of air quality conditions may influence thermal preference. Additionally, AQV is negatively correlated with air movement preference (AMP), $r = -0.193$, $p = 0.001$.

The results of this study contribute information regarding student and teachers perceptions and preferences of their classroom environments, to the body of knowledge that was previously lacking.

CHAPTER VI

CONCLUSIONS

This thesis investigated thermal comfort and indoor air quality conditions in primary school settings, through field surveys, during fall and winter season in the city of Concepción, Chile. The overall aim is to advance our understanding of students' and teachers' sensations towards thermal comfort and indoor air quality, specifically, to identify other factors that might influence their perceptions of thermal comfort and air quality conditions.

The main conclusion of this study is that students and teachers in free-running classrooms feel comfortable in and accept cold and poor air quality conditions, outside the ranges of comfort zone specified by the adaptive model of the ASHRAE–55 (2017) standard, and thresholds of indoor air quality guidelines by WHO (2010) and ASHRAE – 62.1 (2016).

Occupants in this climate zone have found personal ways to adapt themselves to outdoor temperatures lower (<10ºC) than those specified by ASHRAE-55 adaptive model in free-running environments (i.e., limited heating in winter). Prevailing mean outdoor temperature ranges for this study were between 8ºC and 11ºC in fall, and 6 and 9ºC in winter.

The fact that occupants in this cultural and climate region can adapt to comfort in free-running classrooms, with limited opportunities to change indoor environmental conditions, suggests opportunities to expand the adaptive comfort zones to broader ranges of colder outdoor temperatures for school buildings. This offers an excellent possibility for schools to save energy with well-designed characteristics of naturally–ventilated environments that can promote health, performance, and well-being.

This chapter discusses key conclusions drawn from the study based on the research question asked and it suggests further work.

1. ***Physical conditions*****,** such as air temperature, relative humidity, particulate matter, air velocity, CO_2 levels**,** inside learning spaces are deficient (i.e., high CO_2 and particulate matter concentrations, low indoor operative temperatures, and high RH), which confirms results from previous studies in Chilean primary schools (Armijo, Whitman, 2011; Soto et al., 2015; Trebilcock et al., 2017a). However, this study contributes with new knowledge on these conditions, which were seen across all three main types of schools present in the Chilean educational system (i.e., public, private-subsidized, and private–nonsubsidized schools). This evidences the need to incorporate new standards and guidelines that can help to set minimum thresholds for school building design currently unavailable, similar to what developed countries have defined, to provide better indoor conditions in classroom spaces for their occupants.

Concerning measurements of high CO_2 concentrations in all schools, these are likely the result of poor ventilation rates (on average 0.09 m/s in both seasons) and crowded environments, thus limiting the possibilities to remove air pollutants and provide clean air inside the classrooms. CO_2 concentrations average 1600 ppm in fall and 1900 ppm in winter, exceeding the maximum threshold of 1,000 ppm in densely occupied spaces according to EPA and ASHRAE Standard 62.1-2016. Similarly, high particle concentrations for particulate matter PM_{10} were observed. Average concentration in all classroom were 105 μg/m^3 and 117 μg/m^3 in fall and winter, respectively. Average concentrations of PM2.5 were 38 μg/m^3 and 56 μg/m^3 in fall and winter, respectively, thus exceeding WHO 2010 guidelines of 20 μg/m^3 at eight hour mean for PM_{10} and 10 μg/m^3 at eight hour mean for $PM_{2.5}$. These alarming conditions must be address soon because of the effects they can have on children's developmental years, particularly because of the extended hours that children spend indoor. Further research is required in this area, particularly on the effects it can have on health and performance on students and teachers.

2. ***Differences between schools*** were seen as shown in Figure 5.7. High levels of RH (between 65% and 80% on average) and low indoor temperatures (between 15ºC and 24ºC) were measured in public schools compared to both types of private schools.

The social background does have an impact on the current physical conditions measured in the field study; public schools have minimal operational funds administered by municipalities compared to private schools that have more resources due to students tuitions. Construction systems in public schools are mostly outdated compared to private ones. Public schools have basic construction solutions, no insulation, leaky envelopes, many have not been re-conditioned since they were built in the '90s. Little improvements over time and declining enrollment over the years have led parents to consider those public institutions as unfavorable places to send their kids to.

Thermal perceptions and preferences among students and teachers fall within 80% to 90% acceptability (i.e., when asked directly and indirectly through votes calculations) and were mainly distributed within the three central categories of ASHRAE–7 point scale. Their thermal sensation votes had similar normal distributions, with no major differences among their means, except for teacher's votes been skewed to the slightly cool side of the scale, during winter. As evidenced in the study, their thermal sensation votes do respond to outdoor conditions, i.e., when outdoor temperatures were lower, their votes move to the slightly cold part of the scale. This was more evident at the end of the fieldwork when outdoor temperatures were even lower. The latter proves that adaptation is related to outdoor conditions and that children, as well as adults, are aware of weather condition, as the adaptive model defines it.

Even though outdoor and indoor temperatures are low compared to other studies, students (or their parents) and teachers in Chilean schools do accommodate for comfort, through clothing adaptations. Even with strict dress code policies, such as school uniforms, it was evident that their clothing values were significantly higher than in previous studies. Clo values from this study ranged between 0.95 and 1.24 in fall and winter for both students and teachers. However, as evidenced during the campaigns, many students and teachers wore parkas inside the classroom, scarves, mittens, and in some cases wool hats, in which clo values could reach as high as 1.66 to 1.86.

Another potential explanation for why students found thermal conditions comfortable, as noted in the literature, is that students have high metabolic rates and are involved in active school activities in which they are continually interacting with the outdoor environment, making them more aware of those conditions that are much different from those of an office setting where an adult is mostly in sedentary positions.

As observed in fieldwork, students would instead prefer to feel a bit colder or cold, in order to get fresh outdoor air circulation to accommodate slightly stale or stale indoor air, due to their crowded classrooms and low ventilation rates.

It was also acknowledged in the interviews that many teachers withstand cold thermal conditions in the classroom to accommodate for their students' thermal sensation, meaning, they will tolerate cold temperature by opening a window in cold days, so their students would not be feeling warm or hot, and the stuffiness of the environment would be reduced. This has not been evidenced in the literature, and it has been argued that classroom conditions are predominantly controlled and changed based on teachers' thermal sensation. However, this cannot be generalized for all the schools surveyed in this study. Nonetheless, it evidences the awareness that teachers have on their student's comfort and well-being.

Perceptions of IAQ did show some differences between students and teachers. Study results showed that teachers are more sensitive to stuffy/stale conditions than children. This may result from children being permanent residents of their classroom environments. As mentioned before, primary school students in Chilean classrooms are taught the majority of the subjects in the same classroom all day, for an entire year. Therefore, students get acclimated to unsatisfactory conditions, or as other authors have noted, children are not able to perceive or acknowledge poor conditions such as high CO_2 concentration (Fisk, 2017; P. Wargocki & Da Silva, 2015). The latter raises even more concerns due to high concentrations to which they are exposed, and the fact that children might not always be able to report. Further research is required in this area to better understand the consequences on children of long-term exposure to poor IAQ conditions. On the other hand, teachers move around from one environment to another, thus explaining their sensitivity and awareness to poor air quality and also indoor temperatures.

3. ***Perceptions of children between school types*** do differ. Differences were observed between private-subsidize and public schools, and also between private-subsidize and private-nonsubsidized schools. These can be explained by the more modern construction solutions on the private-subsidized schools compare to the other schools and also by the available environmental opportunities to control classroom spaces.

In terms of environmental adaptations, students, as well as teachers, have minimal opportunities to control their indoor classroom conditions, due to the lack of adaptive design strategies of school design. They are only limited to open or close windows and doors, to provide fresh air or change indoor temperatures.

In all public schools, heating systems are not installed or in working condition to accommodate for cold winter temperatures. However, this was different in most private schools since they all have heating systems available in each classroom. As evidenced in the field visits, heating systems, for the most part, are centrally controlled so teachers and students could not change the thermostat. Additionally, many schools heating system were not working correctly or were providing heat when it was no longer needed. The heating systems were very inefficient and affected the thermal perception of occupants.

From focus group interviews and field observations, private school students were more outspoken about their classroom conditions than public school students and would ask the teacher to open/close windows, as well as, to make personal adaptations of clothing, or to bring hot drinks to their classroom to keep themselves warm. On the other hand, public school students were less outspoken about their classroom conditions to their teachers. This might be explained by their experience of emotional deprivation of childhood, due to their low–income social background as compared to the middle and high social backgrounds, which can be seen in both private schools. The latter needs to be further investigated to determine other factors that can influence their perception, as well as, their different means of adaptation.

Overall, the methods implemented to survey this age group of children proved to be successful. Particularly, the use of tablets and measuring equipment helped to get students engaged in the survey activity. Data collection of physical measurements and surveys became a teaching moment for primary school children, especially in deprived backgrounds as these devices are not typical for children to see. Thus, field surveys became a great break and distraction to their regular classroom routine. However, as evidenced in the field campaigns, certain concepts and terminology can still be better improved. Children many times did not understand the concept of air movement, or neutral. To answer these questions, the author provided feedback and explanation during the surveys, to help students to understand what was asked.

6.1. Future work

Work in this area may be expanded in different ways. There are three suggestions that emerge and that I would like to pursue further from this research.

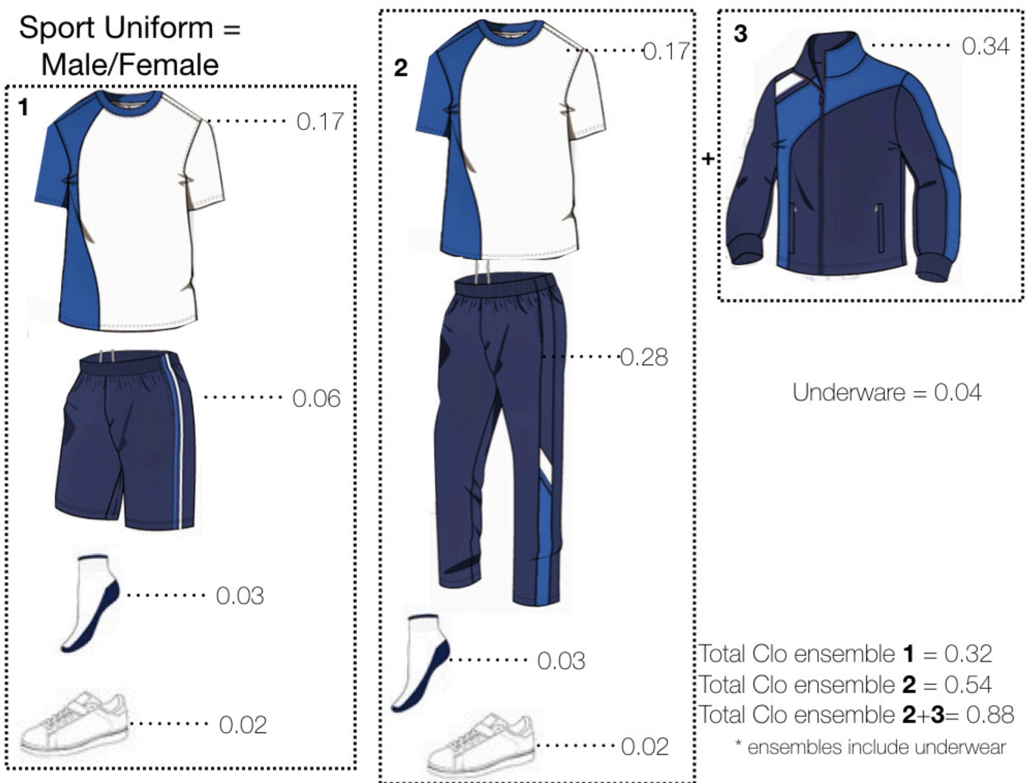
Future work can evaluate classroom conditions in warmer outdoor temperature regimes, i.e., end of spring or end of the summer season, to determine what are the indoor classroom conditions and the different methods of adaptations that students and teacher take?. Because this study only looked at relatively cold outdoor temperatures, questions arise for what it could be the thermal sensation and preferences for students and teacher in warmer conditions. Would they respond the same as they did for this study?. The literature review suggests that children are more sensitive to warmer temperatures, but still manage to adapt to warmer outdoor temperatures, particularly in hot arid climate zones like the middle east.

Deficient IAQ was found in all classrooms spaces, across all different school types. It raises questions about the concerning effects is can have on students' performance, health, and well–being as evidenced in the literature. Future research should look at the effects of high particle and CO_2 concentrations on students' attendances and task performance to determine if associations exist, and what type of effects has on students and teacher. Due to the 2015 national declaration of a saturated zone for fine particle outdoor concentrations in the city of Concepción, a new plan for decontamination would be put in place at the end of this year 2019. Therefore, it would be essential to provide a baseline to evaluate the impact of existing classroom conditions have on performance and health before this plan is put into place, to evaluate later how the implementation of the new plan can impact or not classroom conditions.

As evidenced in the literature as well as in this study, indoor classroom conditions need re-conditioning and retrofitting. School building stock is outdated in terms of classroom design, with layouts from the '70s, that does not incorporate new teaching pedagogies, passive strategies that can provide better and efficient indoor conditions. From this study, new research can look at retrofitting strategies that can integrate all different environmental parameters. The integration of passive and active energy-efficient strategies should be further explored in classroom environments to provide solutions for how we can improve existing school buildings. The development of recommendations for new policy solutions that can address design and building operation of schools should take place. My intension is that this study and my future involvement in this matter can help to move forward to healthier, efficient Chilean schools.

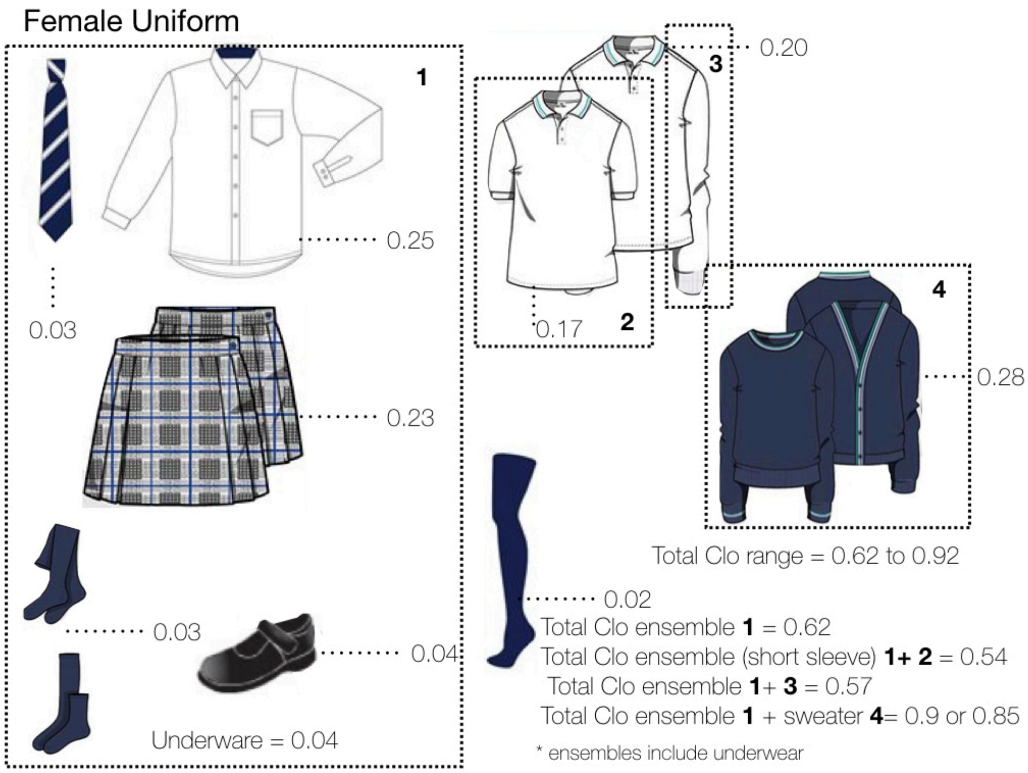
APPENDIX A
INSULATION CALCULATIONS

Calculations of insulation cloth values of students' uniforms



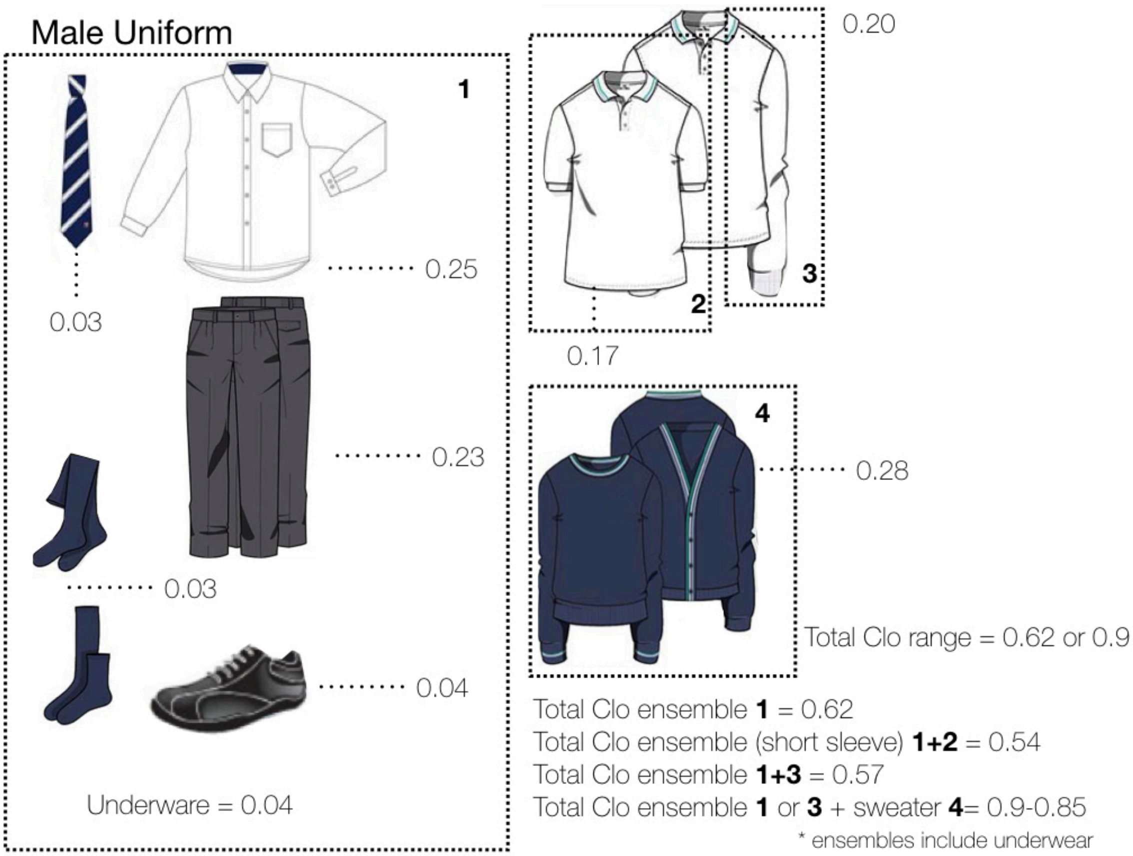
APPENDIX B
INSULATION CALCULATIONS

Calculations of insulation cloth values of students' uniforms



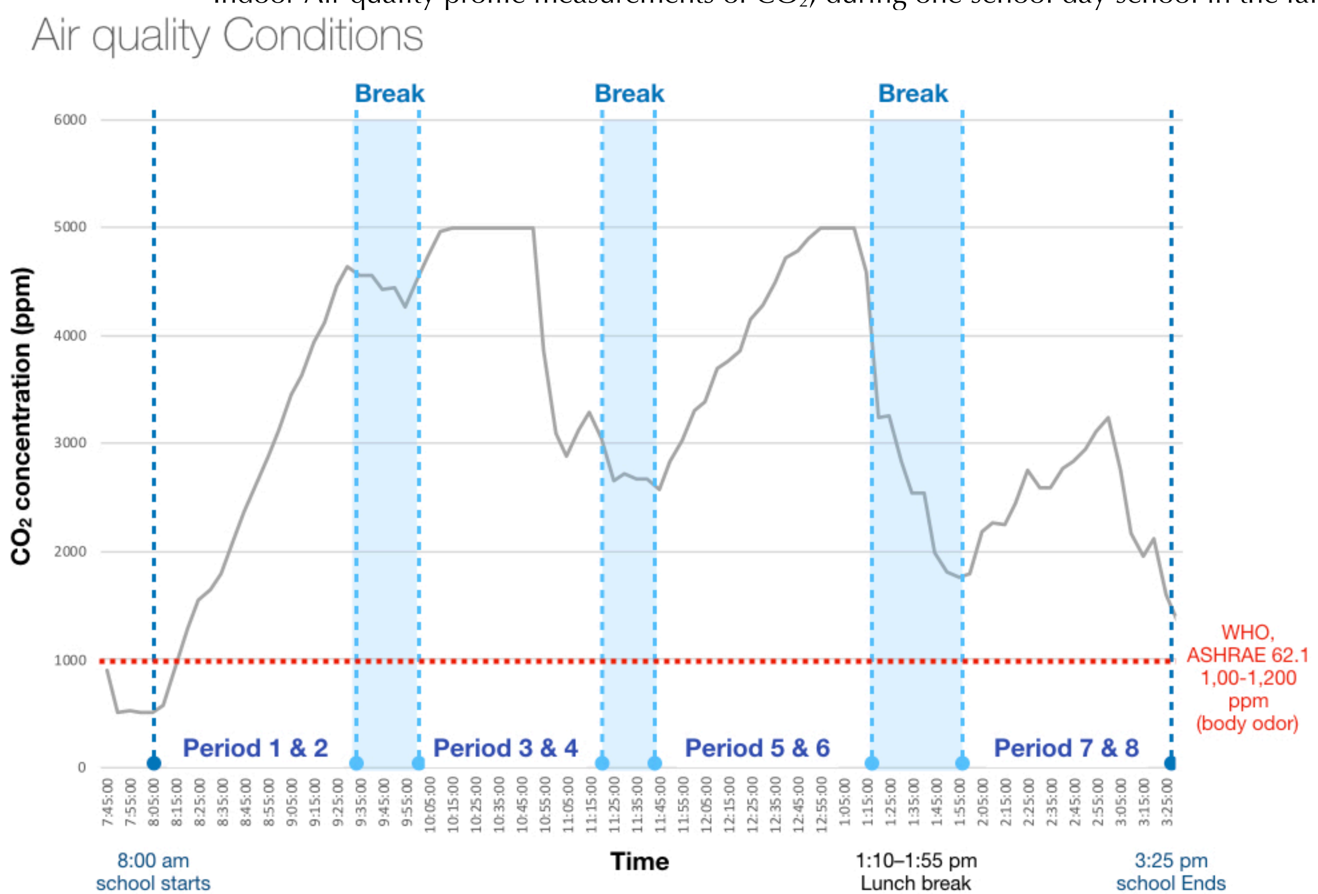
APPENDIX C
INSULATION CALCULATIONS

Calculations of insulation cloth values of students' uniforms



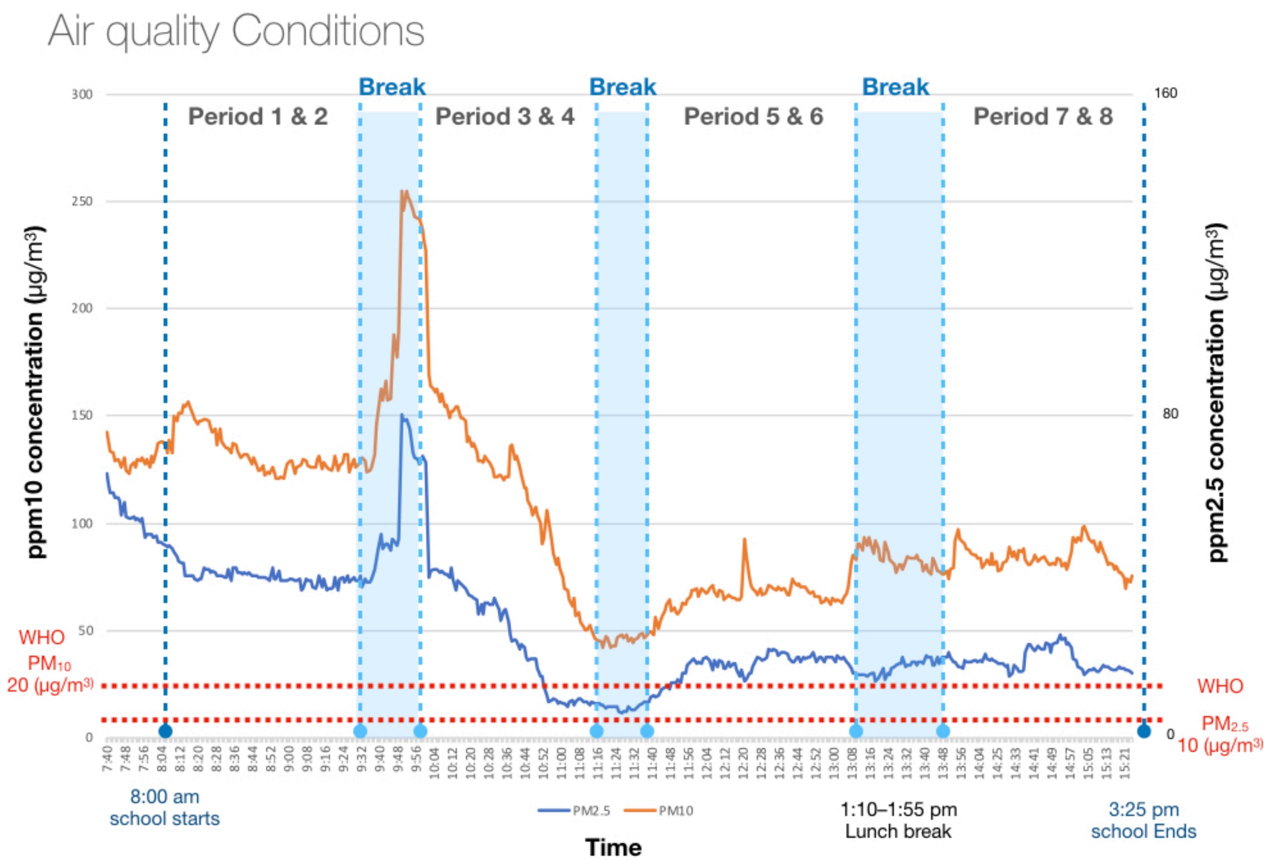
APPENDIX D
INDOOR AIR QUALITY PROFILE MEASUREMENT

Indoor Air quality profile measurements of CO_2, during one school day school in the fall.



APPENDIX E
INDOOR AIR QUALITY PROFILE MEASUREMENT

Indoor Air quality profile measurements of $PM_{2.5}$, and PM_{10} during one school day school in fall.



APPENDIX F
IRB APPROVALS

Notice of IRB Review and Approval, from the Committee for Protection of Human Subjects (CPHS), the University of Oregon Institutional Review Board (IRB).

UNIVERSITY OF OREGON

DATE: December 15, 2017 IRB Protocol Number: 11202017.027

TO: Maria Rivera, Principal Investigator
Department of Architecture & Interior Architecture

RE: Protocol entitled, "Classroom Indoor Environmental Quality "through the eyes" of children"

Notice of IRB Review and Approval
Expedited Review as per Title 45 CFR Part 46 # 6, 7

The project identified above has been reviewed and approved by the Committee for Protection of Human Subjects (CPHS), the University of Oregon Institutional Review Board (IRB). This research has been determined to be no greater than minimal risk and qualifies for expedited review procedures.

For this research, the following additional determinations have been made:

- The study as described satisfies the requirements for additional protections for children involved as subjects in research under 45 CFR Part 46.404.
- The IRB has waived the requirement to obtain parental permission under 45 CFR 46.116(d) to allow for the use of the "passive consent" procedure described in the study materials.

Contingency:

- Since this research will be conducted in a language other than English, translated consent and assent forms will need to be submitted to RCS once obtained.

The IRB has approved the research to be conducted as described in the attached materials. As a reminder, it is your responsibility to submit any proposed changes for IRB review and approval prior to implementation.

Approval period: December 15, 2017 - December 14, 2018

If you anticipate the research will continue beyond the IRB approval period, you must submit a request for continuing review approximately 60 days prior to the expiration date. Without continued approval, the protocol will expire on December 14, 2018 and human subject research activities must cease. A closure report must be submitted once human subject research activities are complete. Failure to maintain current approval or properly close the protocol constitutes non-compliance.

You are responsible for adhering to the *Investigator Agreement* submitted with the initial application for IRB review. The responsibilities of the agreement are reiterated at the end of this letter below. You are responsible for conduct of the research and must maintain oversight of all research personnel to ensure compliance with the IRB approved protocol.

COMMITTEE FOR THE PROTECTION OF HUMAN SUBJECTS ● RESEARCH COMPLIANCE SERVICES
677 E. 12th Ave., Suite 500, 5237 University of Oregon, Eugene OR 97401-5237
T 541-346-2510 F 541-346-5138 **http://rcs.uoregon.edu**

UNIVERSITY OF OREGON

The University of Oregon and Research Compliance Services appreciate your commitment to the ethical and responsible conduct of research with human subjects.

Sincerely,

Christina Spicer, J.D., C.I.P.

INVESTIGATOR AGREEMENT *Principal Investigator and Faculty Advisor Responsibilities*

A. Conduct of the Research

1. I accept responsibility for the ethical conduct of this research and protection of participants as set forth in the Belmont Report, Declaration of Helsinki, the Nuremberg Code, the Common Rule, and the ethical principles of my discipline.
2. I accept responsibility for the conduct of this research ensuring this research is conducted according to
    a. sound research design and methods;
    b. the IRB approved protocol including the informed consent process;
    c. the applicable terms of the grant, contract and/or signed funding agreements; and
    d. applicable laws and regulations, including those for protecting the rights, safety, and welfare of human subjects.
3. I certify that I am or my faculty advisor is sufficiently qualified by education, training, and/or experience to assume responsibility for the proper conduct of this research. I accept responsibility for ensuring that members of this research team, including study staff and trainees, are appropriately qualified, trained and supervised.
4. I accept responsibility to personally conduct and/or directly supervise this research. I certify that I have sufficient time and resources to properly conduct and/or supervise this research for which I am responsible.

B. Ensuring and Maintaining Compliance

1. I will comply with relevant regulatory and institutional requirements, including those relating to conflicts of interest, responsible conduct of research and research misconduct.
2. I understand it is my responsibility to ensure that any research personnel, including myself, responsible for the design, conduct, and reporting of research declare any potential conflicts of interests related to the research and to maintain current records. I will ensure changes in conflicts of interest are promptly disclosed to the IRB.
3. I will ensure that informed consent is obtained as approved by the IRB and a copy is provided to participants, unless the IRB waives these requirements.
4. I will obtain initial IRB approval prior to implementing human subject research activities as well as prior approval for any amendments to this research.

COMMITTEE FOR THE PROTECTION OF HUMAN SUBJECTS ● RESEARCH COMPLIANCE SERVICES
677 E. 12th Ave., Suite 500, 5237 University of Oregon, Eugene OR 97401-5237
T 541-346-2510 F 541-346-5138 **http://rcs.uoregon.edu**

INVESTIGATOR AGREEMENT

Principal Investigator and Faculty Advisor Responsibilities

5. I will conduct this research within the approval period issued by the IRB. I agree to submit a request for continuing review of this research at least 45 days in advance of the expiration date.
6. I will submit a closure report form prior to protocol expiration or within 45 days of completion of all activities involving human subjects or identifiable participant data.
7. I will maintain approval, as applicable, with collaborative entities including approvals from other countries or jurisdictions.
8. I will promptly report to the IRB (no later than seven days of discovery) any instances of noncompliance with the approved protocol or requirements of the IRB and any unanticipated problems.
9. I will assist in the facilitation of any monitoring and/or auditing of study activities and/or records as required by the IRB, funding entities, sponsors, and any federal and state regulatory agencies.

C. Investigator Records, Reports and Documentation

1. I will maintain research records, all protocol materials, and any other documents associated with this research (e.g., research plan, signed consent forms, and IRB correspondence).
2. I will maintain records for at least three years after this research ends, or for the length of time specified in applicable regulations or institutional or sponsor requirements, whichever is longer. I will take measures to prevent accidental or premature destruction of these documents.
3. I will ensure the safe and secure storage of this research data (whether in paper or electronic formats) and for protecting the confidentiality of the data in accordance with the approved protocol.
4. I will submit written reports to the IRB and permit inspection of the research records as required by the IRB.

COMMITTEE FOR THE PROTECTION OF HUMAN SUBJECTS ● RESEARCH COMPLIANCE SERVICES
677 E. 12th Ave., Suite 500, 5237 University of Oregon, Eugene OR 97401-5237
T 541-346-2510 F 541-346-5138 **http://rcs.uoregon.edu**

APPENDIX G
IRB APPROVALS

Notice of IRB Review and Approval, from the Ethics Committee "Comité de Etica, Bioetica y Bioseguridad" of the Vicerrectoria de Investigación y Desarrollo, University of Concepción.

Universidad de Concepción

Concepción, enero de 2018.

CERTIFICADO

El Comité de Ética, Bioética y Bioseguridad de la Vicerrectoría de Investigación y Desarrollo de la Universidad de Concepción ha revisado el protocolo del **PROYECTO DE TESIS**, titulado "**CALIDAD AMBIENTAL AL INTERIOR EN LAS SALAS DE CLASES, UNA VISIÓN DESDE LOS NIÑOS**" postulado por la Profesora Asistente Departamento de Arquitectura de la Universidad de Concepción, **SRTA. MARÍA ISABEL RIVERA B.**, en calidad de candidata al grado de Doctor, junto a su Profesora Guía, **DRA. ALISON KWOK**, docente de IA School of Architecture & Environment de la University of Oregon, U.S.A, y ha comprobado que cumple con las normas, procedimientos éticos y los principios bioéticos establecidos nacional e internacionalmente para estudios que involucran personas.

La presente propuesta de Proyecto de Tesis para la obtención del grado de Doctor por la University of Oregon, tiene como objetivo conocer la percepción de alumnos de 6º a 8º básico (de 11 a 14 años de edad) y sus correspondientes profesores (un profesor por curso), de distintos colegios (públicos, subvencionados, y particulares) de las comunas de Concepción y San Pedro de la Paz, en la Región del Bío-Bio, Chile, con respecto a las condicionantes ambientales de sus salas de clases. Para ello, propone desarrollar tres objetivos específicos. Inicialmente propone entender mejor qué tan predecibles son los niños en auto-reportar sus percepciones en los ambientes de salas de clases. Después, buscará caracterizar las condiciones físicas dentro de salas de clases en diferentes temporadas y cómo se comparan con estándares internacionales, como son la ISO 7730 y 10551, y ASHRAE 55-2017. Por último, prevé potenciar la propuesta de expandir la zona de confort para niños según los estándares de confort térmicos mencionados. Para ello, describe en "Metodología y materiales" tres etapas a ejecutar durante el desarrollo de los objetivos: (I) está enfocada en un método cuantitativo, consistente en la medición de parámetros físicos de confort térmico y calidad de aire, como también de la evaluación subjetiva a través de cuestionarios. En esta etapa se tomará dos muestras por temporada (verano, en marzo, e invierno, en junio de 2018); (II) consiste en métodos cualitativos, donde está previsto aplicar entrevistas y realizar visitas a terreno. El objetivo de aplicar estos procedimientos, es poder entender las respuestas de los alumnos y profesores, su percepción y factores personales relacionados a la evaluación de los ambientes de sus salas de clases, y compararlas con los valores detectados por los instrumentos de medición, y (III) incluye la interpretación y análisis de los resultados de las etapas I y II. En esta última etapa se buscará explicar en mayor detalle el problema de la investigación a través de un análisis de triangulación.

UNIVERSIDAD DE CONCEPCIÓN COMITÉ DE ÉTICA

Universidad de Concepción

La participación de cada sujeto seleccionado estará basada en el proceso de Asentimiento Informado y de Consentimiento Informado, toda vez que sean regularmente firmados. Cada proceso será documentado.

La custodia de la información y de los resultados del estudio que se propone será responsabilidad de la Investigadora Responsable, Srta. María Isabel Rivera B.

Es importante destacar que el presente proyecto de tesis para optar al grado de Doctor en la *University of Oregon*, fue evaluado y aprobado por el comité de protección sujetos humanos y ética de la misma institución universitaria (Research Compliance Service - RCS) a través del consejo de revisión institucional (IRB) previo al inicio del estudio en terreno, ahí registrado bajo el Nº 11202017.027, con validez hasta el 14 de diciembre 2018.

La ejecución del proyecto de intervención asegura que no vulnera los derechos y la dignidad de los sujetos participantes en el estudio, garantizando la libertad, la autonomía, la voluntariedad y la privacidad de los mismos, presentando para ello los métodos de protección que aseguran la confidencialidad de los datos de investigación y de custodia estricta de la información obtenida, observando todas las características formales y necesarias para su validez.

Este Comité considera que el proyecto de tesis presentado observa los derechos asegurados en la Declaración Universal de los Derechos Humanos, la Convención sobre los Derechos del Niño, los derechos y principios de la Declaración Universal sobre Bioética y Derechos Humanos, las Normas Éticas de la Organización Panamericana de la Salud para Investigaciones con Sujetos Humanos, la Constitución de la República de Chile, la Ley N° 20.120 "Sobre la Investigación Científica en el Ser Humano, su Genoma y Prohíbe la Clonación Humana" y la Ley N°. 20.584, que "Regula los derechos y deberes que tienen las personas en relación con acciones vinculadas a su atención en salud" y la Ley n° 19.628, "Sobre Protección de la Vida Privada".

En atención a lo anterior y dado que el proyecto de tesis presentado no muestra elementos que puedan transgredir las normas y principios éticos y bioéticos de la investigación en seres humanos, así también los principios rectores de nuestra Institución Universitaria y los delineados en la Declaración de Singapur sobre la Integridad en la Investigación (2010), este Comité resuelve aprobarlo, confiriendo el presente Certificado.

DR. JOSÉ BECERRA ALLENDE
COMITÉ DE ÉTICA, BIOÉTICA Y BIOSEGURIDAD
VICERRECTORÍA DE INVESTIGACIÓN Y DESARROLLO
UNIVERSIDAD DE CONCEPCIÓN

UNIVERSIDAD DE CONCEPCIÓN
COMITÉ DE ÉTICA

APPENDIX H
QUESTIONNAIRE

Student questionnaire example.

UNIVERSITY OF OREGON

Proyecto: Calidad ambiental interior en las salas de clases, una visión desde los niños.

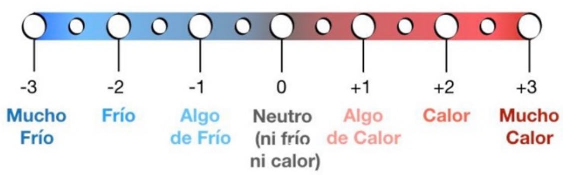
Universidad de Concepción

Curso #:__________
Día:__________
Hora:__________
Nº:__________

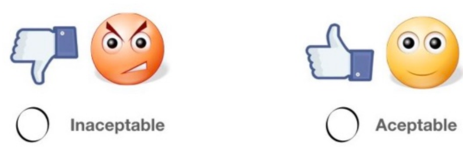
Cuestionario de Confort Térmico y Calidad del Aire para Estudiantes

Parte I: *las siguientes preguntas te van a consultar sobre tu estado de confort personal en este preciso momento en tu sala de clases.*

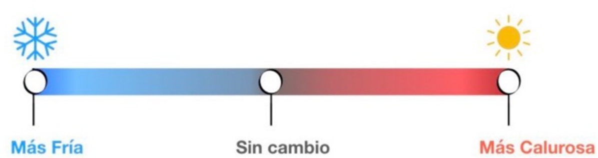
P1) ¿Cómo te sientes en este **momento**? Yo tengo:
(Recuerda solo marcar un circulo sobre la escala)



P2) ¿Cómo percibes la **temperatura** en la sala de clases en **este momento**?



P3) En este momento, ¿Cómo **prefieres** la temperatura en la sala de clases?
(Recuerda solo marcar un circulo sobre la escala)



P4) Ahora, ¿tú sientes circulación de aire en la sala de clases? **(Recuerda solo marcar una opción)**

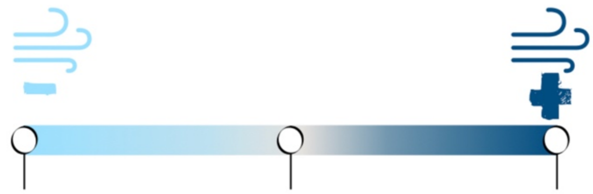
- ○ Si
- ○ No

[Rivera] [Protocolo Nº11202017.027] [V3_12/15/2017] Página 2 de 9

P5) En este momento la circulación de aire es:

◯ Inaceptable ◯ Aceptable

P6) En este momento, ¿Cómo prefieres que sea la circulación de aire? **(Recuerda solo marcar un circulo sobre la escala)**



P7) Por favor indica en la escala de abajo ¿Cómo sientes tú la calidad del aire ahora en tu sala de clases? **(Recuerda solo marcar un circulo sobre la escala)**

P8) ¿Cómo clasificarías el olor en la sala de clases ahora? **(Recuerda solo marcar una opción)**

◯	Sin olor
◯	Olor moderado
◯	Olor intenso
◯	Olor muy intenso
◯	Olor insoportable

P9) Los olores que percibes, ahora, en tu sala de clases son un problema:

◯	**Sí,** son un problema
◯	**No**, no son problema

P10) Si existe un problema de olor en la sala de clases, ¿cuál o cuáles de los siguientes factores producen estos olores? **(Selecciona todos los que aplican)**

○ Comida	○ Olores corporales
○ Perfume	○ Productos de limpieza
○ Pintura o barniz de muebles o muros	○ Plumones de pizarra
○ Humo de automóviles	○ Smog (humo de combustión)
○ Polvo	○ Humo de cigarrillos
○ Otro:	

P11) Por favor marca en la siguiente lista cada elemento de **vestuario** que estas ocupando en **este momento** (marca todos los que correspondan):

○ Camina manga larga	○ Polerón	○ Calcetines
○ Polera	○ Chaqueta	○ Zapatos
○ Camiseta	○ Falda	○ Botas/Bototos
○ Ropa interior de invierno (calzas y/o calzoncillos largos)	○ Pantalón de tela	○ Zapatillas
○ Cotono/Delantal	○ Pantalón de buzo	○ Bufanda / Cuello
○ Chaleco	○ Shorts	○ Gloves | Guantes
○ Polar	○ Medias	○ Gorro

Parte II: *las siguientes preguntas se refieren a tu satisfacción personal y síntomas que hayas experimentado en las semanas o mes pasado de tu sala de clases y en tu casa. Para esto te pediremos que compares tu sala de clases con tu casa.*

P12) ¿Dónde tú te sientes mejor? Con respecto a: (Marca **solo una** alternativa por fila-horizontal)

	Sala de clases	**Casa**	**Ambos**	**Ninguno**
Temperatura Interior	○	○	○	○
Circulacion de aire interior	○	○	○	○
Calidad de aire interior	○	○	○	○
Humedad interior	○	○	○	○
Nivel de ruido	○	○	○	○
Olores	○	○	○	○

P13) Piensa ¿cómo te has sentido en las semanas anteriores? y responde las siguientes afirmaciones.

	Siempre	**Casi siempre**	**La mitad del tiempo**	**Algunas veces**	**Nunca**
Me sentí acalorado	○	○	○	○	○
Sentí frío	○	○	○	○	○
Sentí Olores desagradables	○	○	○	○	○
Tuve Problemas para respirar (Nariz tapada)	○	○	○	○	○
Me Sentí con sueño y cansado	○	○	○	○	○
Tuve Dolor de Cabeza	○	○	○	○	○
Sentí los Labios y Piel seca	○	○	○	○	○
Tuve Sequedad en ojos y/o irritación	○	○	○	○	○
Tuve la Garganta seca	○	○	○	○	○

P14) A la fecha, ¿Cuántos días has faltado a clases producto de resfríos y/o influenza

NInguno	**1 día**	**2 a 5 días**	**5 a 8 días**	**Más de 10 días**
○	○	○	○	○

Q15) ¿Sufres de asma?

- ◯ **Sí**
- ◯ **No**

Parte III: *las siguientes preguntas se refieren a información general sobre las condiciones de tu casa.*

P16) ¿Tienes un sistema de calefacción en casa?

- ◯ **Sí**
- ◯ **No**

P17) Si la respuesta es sí, ¿de qué tipo? (marca todas las que utilizan)

- ◯ Calefactor eléctrico
- ◯ Estufa a gas
- ◯ Estufa a parafina
- ◯ Estufa a leña o pellet
- ◯ Chimenea
- ◯ Brasero
- ◯ Calefacción Central
- ◯ No tengo sistema de calefacción

P18) ¿Hay personas de tu familia que fuman dentro de tu casa?

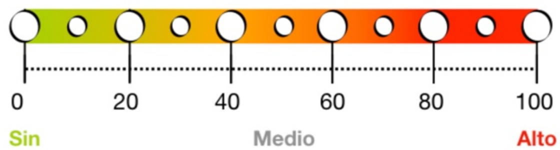
- ◯ **Sí**
- ◯ **No**

P19) Si la respuesta es sí, ¿Qué tan seguido?

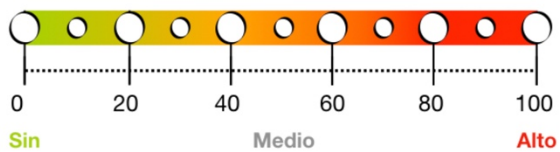
Diariamente	**Cada semana**	**Una vez por mes**	**Solo en ocasiones sociales**
◯	◯	◯	◯

Parte IV: *en las siguientes preguntas tú vas a evaluar el impacto que las condiciones ambientales de tu sala de clases generan en tu aprendizaje.*

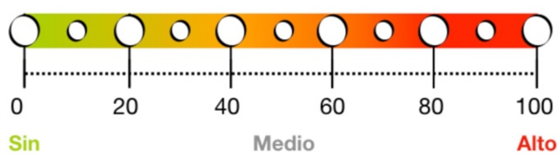
P20) Evalúa el grado en que tú piensas la temperatura impacta en tu aprendizaje. **(0 sin impacto y 100 para alto impacto)**



P21) Evalúa el grado en que tú piensas la **Calidad del Aire** de tu sala de clases **impacta** en tu **aprendizaje**. **(0 sin impacto y 100 para alto impacto)**



P22) Evalúa el grado en que las condiciones de iluminación (habilidad de poder ver la pizarra, proyector, tu área de trabajo, libros/cuadernos, etc.) afectan tu **aprendizaje**. **(0 sin impacto y 100 para alto impacto)**



P23) Cuándo las condiciones ambientales no son adecuadas para ti, y te sientes incomodo en la sala de clases, ¿Cómo afecta en tu aprendizaje? **(Por favor selecciona una sola opción)**

- ◯ Dificultad para concentrarme (tener sueño, tener frio o calor)
- ◯ No puedo puedo participar en clases (tomar apuntes y/o participar en forma oral)
- ◯ Me cuesta entender lo que se me está enseñando
- ◯ Todas las anteriores
- ◯ No tiene ningún efecto en mi

P24) No puedo desempeñarme de la mejor manera en el colegio cuando:
(Por favor selecciona una sola opción)

- ◯ Cuando siento calor
- ◯ Cuando siento frío
- ◯ Cuando siento el aire pesado
- ◯ Cuando siento humedad (vidrios y/o muros húmedos)
- ◯ Todas las anteriores
- ◯ Siempre puedo desempeñarme bien bajo cualquier condición

P25) ¿Qué condiciones ambientales (temperatura, humedad, circulación y calidad del aire, iluminación y ruido) agregarías y/o modificarías de tu sala de clases para aprender mejor?

____

____

____

***Parte V**: Demografía*

P26) Género

- ◯ Femenino
- ◯ Masculino

P27) ¿Tienes nacionalidad es chilena? Si no, ¿Cuál es tu nacionalidad?

- ◯ Sí
- ◯ No,

P28) ¿Cuál es tu edad? (selecciona lo más cercano)

◯ 10 años ◯ 11 años ◯ 12 años ◯ 13 años ◯ 14 años ◯ 15 años
◯ 16 años ◯ 17 años ◯ 18 años ◯ Otro

P29) ¿Cuál es tu altura? (metros)

◯ 1.30 a 1.40 mt ◯ 1.40 a 1.50 mt ◯ 1.50 a 1.60 mt ◯ 1.60 a 1.70 mt ◯ 1.70 a 1.80 mt

P30) ¿Cuál es tu peso? (kilos)

○ 30 a 35 kilos	○ 35 a 40 kilos	○ 40 a 45 kilos	○ 45 a 50 kilos	○ 50 a 55 kilos	○ 55 a 60 kilos
○ 60 a 65 kilos	○ 65 a 70 kilos	○ 70 a 75 kilos	○ 75 a 80 kilos	○ > de 80 kilos	

P31) ¿Por cuánto tiempo has estado en este colegio? (selecciona en siguiente menú)

○ < de 1 año	○ 1 año	○ 2 años	○ 3 años	○ 4 años	○ 5 años	○ 6 años
○ 7 años	○ 8 años	○ 9 años	○ 10 años	○ > de 10 años		

P32) ¿En qué tipo de vivienda vives?

○ Departamento ○ Casa aislada ○ Casa pareada

P33) ¿Cuál es el nivel de educación de tus padres?

○ Enseñanza Media completa

○ Instituto Profesional o Centro de formación técnica completa

○ Universidad completa

○ Ninguna

○ No se

P34) ¿En qué categoría crees tú se ajusta mejor el sueldo anual de tu familia?

○ Sueldo bajo ○ Sueldo medio ○ Sueldo alto

P35) Finalmente, ¿Quisieras participar en la etapa II (entrevista junto a un grupo de tus compañeros).

○ **Sí**

○ **No,**

P36) Si la respuesta es **Si,** ¿Puedes compartir tu información de contacto?

Nombre ____

Correo electrónico ____

Número de teléfono ____

¡Gracias por responder esta encuesta!

REFERENCES CITED

Academie, J. V. E. (2006). *Going aerial: air, art, architecture*. (M. Bakkle, Ed.).

Ahmed Abdul–Wahab, S. A., En, S. C. F., Elkamel, A., Ahmadi, L., & Yetilmezsoy, K. (2015). A review of standards and guidelines set by international bodies for the parameters of indoor air quality. *Atmospheric Pollution Research*, *6*(5), 751–767. https://doi.org/10.5094/APR.2015.084

Al-hemoud, A. M. (2017). International Guidelines and Standards Pertaining to Indoor Air Quality, (April).

Amato, F., Rivas, I., Viana, M., Moreno, T., Bouso, L., Reche, C., … Querol, X. (2014). Sources of indoor and outdoor PM2.5 concentrations in primary schools. *Science of the Total Environment*, *490*, 757–765. https://doi.org/10.1016/j.scitotenv.2014.05.051

ASHRAE, *ANSI/ASHRAE* Standard 55-2004. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.: Atlanta, GA).

ASHRAE*, ANSI/ASHRAE* Standard 55-2017. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.: Atlanta, GA).

ASHRAE, *ANSI/ASHRAE* Standard 62.1-2016. Ventilation for acceptable indoor air quality. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.: Atlanta, GA.

ASHRAE, *ANSI/ASHRAE 2017 ashrae handbook* (Inch-pound ed., Vol. , fundamentals) [Inch-pound edition.]. Atlanta, GA: ASHRAE, 2017

ASHRAE-IWEC. (2001). International Weather for Energy Calculations (IWEC) Users Manual and CD-ROM. Atlanta: ASHRAE.

Armijo, Whitman, C. (2011). Post-occupancy evaluation of state schools in 5 climatic zones of Chile. *Gazi University Journal of Science*, *24*(2), 365–374.

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *International Journal of Biometeorology*, *25*(2), 109–122. https://doi.org/10.1007/BF02184458

Baker, L. (2011). *Center for the Built Environment UC Berkeley*. UC Berkeley. https://doi.org/10.1016/j.enbuild.2013.06.009.Keywords

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

Benzinger, T. (1979). The physiological basis for thermal comfort. *Indoor Climate*, 441–476. Retrieved from https://scholar.google.com/scholar_lookup?title=The physiological basis for thermal comfort&publication_year=1979&author=T.H. Benzinger

Bernstein, J. A., Alexis, N., Bacchus, H., Bernstein, I. L., Fritz, P., Horner, E., … Tarlo, S. M. (2008). The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*, *121*(3), 585–591. https://doi.org/10.1016/j.jaci.2007.10.045

Bluyssen, P. M., Roda, C., Mandin, C., Fossati, S., Carrer, P., de Kluizenaar, Y., … Bartzis, J. (2016). Self-reported health and comfort in "modern" office buildings: First results from the European OFFICAIR study. *Indoor Air*, *26*(2), 298–317. https://doi.org/10.1111/ina.12196

Bluyssen, Philomena M. (2012). *The Indoor Environment Handbook*. *Proceedings of the ICE - Engineering Sustainability* (Vol. 165). https://doi.org/10.1680/ensu.10.00054

Brager, G., & Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. *Building Research and Information*, *37*(4), 369–380. https://doi.org/10.1080/09613210902899785

Brager, G. S., & de Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, *27*(1), 83–96. https://doi.org/10.1016/S0378-7788(97)00053-4

Charles K. E. (2003). *Fanger ' s Thermal Comfort and Draught Models IRC Research Report RR-162*. *October*. Ottawa.

Chatzidiakou, L., Mumovic, D., & Dockrell, J. (2014). *The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students Commissioned by:* London.

Chatzidiakou, L., Mumovic, D., & Summerfield, A. J. (2012). What do we know about indoor air quality in school classrooms? A critical review of the literature. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/17508975.2012.725530, *4*(4), 228–259. https://doi.org/10.1080/17508975.2012.725530

Chen, W. L., Shih, Y. C., & Chi, C. F. (2010). Hand and finger dexterity as a function of skin temperature, EMG, and ambient condition. *Human Factors*, *52*(3), 426–440. https://doi.org/10.1177/0018720810376514

CIBSE. (2006). *Environment Design*. *Freelancer's Guide to Corporate Event Design: From Technology Fundamentals to Scenic and Environmental Design*. https://doi.org/10.1016/B978-0-240-81224-3.00016-9

Clements-Croome, D. (2018). *Creating the productive workplace : places to work creatively* (Third ed.). London: Routledge, Taylor & Francis Group.

Cui, W., Cao, G., Park, J. H., Ouyang, Q., & Zhu, Y. (2013a). Influence of indoor air temperature on human thermal comfort, motivation and performance. *Building and Environment*, *68*, 114–122. https://doi.org/10.1016/j.buildenv.2013.06.012

Cui, W., Cao, G., Park, J. H., Ouyang, Q., & Zhu, Y. (2013b). Influence of indoor air temperature on human thermal comfort, motivation and performance. *Building and Environment*, *68*, 114–122. https://doi.org/10.1016/j.buildenv.2013.06.012

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003a). 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

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003b). Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor Air*, *13*(1), 53–64. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12608926

de Dear, & Brager. (1998). Developing an Adaptive Model of Thermal Comfort and Preference -RP 884 final report. *ASHRAE Transactions*, *104*(March), 1–18. Retrieved from https://escholarship.org/content/qt4qq2p9c6/qt4qq2p9c6.pdf

de Dear, R. J., Akimoto, T., Arens, E. A., Brager, G., Candido, C., Cheong, K. W. D., … Zhu, Y. (2013). Progress in thermal comfort research over the last twenty years. *Indoor Air*, *23*(6), 442–461. https://doi.org/10.1111/ina.12046

de Dear, R, Brager, G., & Cooper, D. (1997). Developing an adaptive model of thermal comfort and preference - Final Report on RP-884. *ASHRAE Transactions*, *104*(Part 1), 1–18. Retrieved from http://sydney.edu.au/architecture/documents/staff/richard_de_dear/RP884_Final_Report.pdf%0Ahttp://escholarship.org/uc/item/4qq2p9c6.pdf

de Dear, R, Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in australian school classrooms. *Building Research and Information*, *43*(3), 383–398. https://doi.org/10.1080/09613218.2015.991627

de Dear, R. (2004). Thermal comfort in practice. *Indoor Air*, *14*(Suppl 7), 32-39.

de Dear, R. (1998). A global database of thermal comfort field experiments. Field studies of thermal comfort and adaptation. *ASHRAE Technical Data Bulletin 14*, (January 1998), 15–26.

de Dear, R., & Brager, G. (2002). Thermal comfort in naturally ventilated buildings: revision to ASHRAE standards 55. *Journal of Energy and Buildings*, *34*, 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1

De Giuli, V., Da Pos, O., & De Carli, M. (2012). Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment*, *56*, 335–345. https://doi.org/10.1016/j.buildenv.2012.03.024

EN15251, B. E. 15251:2007. (2007). *EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics* (Vol. 3).

Enander, A. E., & Hygge, S. (1990). Thermal stress and human performance. *Scandinavian Journal of Work, Environment and Health*, *16*(SUPPL. 1), 44–50. https://doi.org/10.5271/sjweh.1823

EPA. (2016). NAAQS Table. Retrieved August 28, 2019, from https://www.epa.gov/criteria-air-pollutants/naaqs-table

Fabbri, K. (2013). Thermal comfort evaluation in kindergarten: PMV and PPD measurement through datalogger and questionnaire. *Building and Environment*, *68*, 202–214. https://doi.org/10.1016/j.buildenv.2013.07.002

Fabbri, K. (2015). *Indoor thermal comfort perception : a questionnaire approach focusing on children*. Berlin : Springer.

Falk, B. (1998). Effects of thermal stress during rest and exercise in the paediatric population. *Sports Medicine*, *25*(4), 221–240.

Fanger, P. O. (1970). *Thermal comfort: Analysis and applications in environmental engineering*. *Applied Ergonomics*. Danmarks Tekniske Høojskole, McGraw Hill Book Company, USA. https://doi.org/10.1016/s0003-6870(72)80074-7

Fisk, W. J. (2017). The ventilation problem in schools: Literature review. *Indoor Air*, (June), 1–13. https://doi.org/10.1111/ina.12403

Fisk, W. (2002). How IEQ affects health, productivity. *ASHRAE Journal*, *44*(5), 56–58.

Frumkin, H. (2006). *Safe and healthy school environments*. Oxford University Press.

Griffiths, I. D. (1991). *Thermal comfort in buildings with passive solar features : field studies.* (C. of the E. Communities, Ed.). Euratom publications - eur, 13431. Retrieved from https://uolibraries.on.worldcat.org/search?queryString=no%3A+59990090#/oclc/59990090

Haddad, S., King, S., Osmond, P., & Heidari, S. (2012). Questionnaire Design to Determine Children's Thermal Sensation, Preference and Acceptability in the Classroom. *Proceedings of 28th PLEA Conference*, *1*(November), 2.

Haddad, Shamila. (2016). *Thermal Comfort in Naturally Ventilated Schools*. The University of New South Wales.

Haddad, Shamila, Osmond, P., & King, S. (2013). Metabolic rate estimation in the calculation of the pmv for children. *47th International Conference of the Architectural Science Association*, 241–250.

Haddad, Shamila, Osmond, P., & King, S. (2017a). Revisiting thermal comfort models in Iranian classrooms during the warm season. *Building Research and Information*, *45*(4), 457–473. https://doi.org/10.1080/09613218.2016.1140950

Haddad, Shamila, Osmond, P., & King, S. (2017b). Revisiting thermal comfort models in Iranian classrooms during the warm season. *Building Research and Information*, *45*(4), 457–473. https://doi.org/10.1080/09613218.2016.1140950

Haddad, Shamila, Osmond, P., & King, S. (2019). Application of adaptive thermal comfort methods for Iranian schoolchildren. *Building Research and Information*, *47*(2), 173–189. https://doi.org/10.1080/09613218.2016.1259290

Halawa, E., & Van Hoof, J. (2012). The adaptive approach to thermal comfort: A critical overview. *Energy and Buildings*, *51*, 101–110. https://doi.org/10.1016/j.enbuild.2012.04.011

Havenith, G. (2007). Metabolic rate and clothing insulation data of children and adolescents during various school activities. *Ergonomics*, *50*(10), 1689–1701. https://doi.org/10.1080/00140130701587574

Haverinen-Shaughnessy, U., & Shaughnessy, R. J. (2015). Effects of classroom ventilation rate and temperature on students' test scores. *PLoS ONE*, *10*(8), 1–14. https://doi.org/10.1371/journal.pone.0136165

Haverinen-Shaughnessy, U., 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

Hensen, J. L. M. (1991). *On the thermal interaction of building structure and heating and ventilation system - (Dissertation) - Technische Universiteit Eindhoven, Netherlands*.

Heschong, L. (1979). *Thermal delight in architecture*. Cambridge, Mass: MIT Press.

Humphreys, Michael, F. N. (1998). Understandng the adaptive approach to Thermal Comfort. *ASHRAE Transactions*, 1–14.

Humphreys, M. A., & Nicol, J. F. (2002a). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, *34*(6), 563–572. https://doi.org/10.1016/S0378-7788(02)00006-3

Humphreys, M. A., & Nicol, J. F. (2002b). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings*, *34*(6), 667–684.

Humphreys, M. A., Rijal, H. B., & Nicol, J. F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment*, *63*, 40–55. https://doi.org/10.1016/j.buildenv.2013.01.024

Hussein, I, & Rahman, M. H. A. (2009). Field study on thermal comfort in Malaysia. *European Journal of Scientific Research*, *37*(1), 134–152. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-70449090056&partnerID=40&md5=108f979d4c4d7f32bc1cd09a9e0895a7

Hussein, Ibrahim, Rahman, M. H. A., & Maria, T. (2009). Field studies on thermal comfort of air-conditioned and non air-conditioned buildings in Malaysia. *ICEE 2009 - Proceeding 2009 3rd International Conference on Energy and Environment: Advancement Towards Global Sustainability*, (December), 360–368. https://doi.org/10.1109/ICEENVIRON.2009.5398622

ISO 10551. (1995). ISO 10551 Ergonomics of the thermal environment–Assessment of the influence of the thermal environment using subjective judgement scales, 1–20.

ISO 7726. (2001). ISO 7726 Ergonomics of the thermal environment — Instruments for measuring physical quantities. *Bs En Iso 7726:2001*, (1), 1–62. https://doi.org/10.3403/02509505

ISO 7730. (2005). ISO 7730 Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

ISO 8996. (2004). ISO 8996: 2004(E) Ergonomics of the thermal environment — Determination of metabolic rate, 1–21. https://doi.org/10.1016/j.jssc.2008.03.003

Joost van Hoof, Mitja Mazej, J. L. M. H. (2010). Thermal comfort: research and practice. *Frontiers in Bioscience*, *15*(2), 765–788.

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

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

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., … Engelmann, W. H. (2001). The National Human Activity Pattern Survey. *Lawrence Berkeley National Laboratory*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165 T4 - A resource for assessing exposure to environmental pollutants Y3 - 20/2/2017 U6 - 10.1038/sj.jea.7500165 M4 - Citavi

Korsavi, S. S., & Montazami, A. (2019). Developing a valid method to study adaptive behaviours with regard to IEQ in primary schools. *Building and Environment*, *153*(February), 1–16. https://doi.org/10.1016/j.buildenv.2019.02.018

Kosonen, R., & Tan, F. (2004). Assessment of productivity loss in air-conditioned buildings using PMV index. *Energy and Buildings*, *36*(10 SPEC. ISS.), 987–993. https://doi.org/10.1016/j.enbuild.2004.06.021

Kovats, R. S., & Hajat, S. (2008). Heat Stress and Public Health: A Critical Review. *Annual Review of Public Health*, *29*(1), 41–55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843

Kwok, A. G. (1997). *Thermal comfort in naturally-ventilated and air-conditioned classrooms in the tropics*. UC Berkeley.

Lan, L., Wargocki, P., & Lian, Z. (2011). Quantitative measurement of productivity loss due to thermal discomfort. *Energy and Buildings*, *43*(5), 1057–1062. https://doi.org/10.1016/j.enbuild.2010.09.001

Leeuw, E. D. de. (2001). Reducing Missing Data in Surveys: An Overview of Methods. *Quality and Quantity*, *35*(2), 147–160. https://doi.org/10.1023/A:1010395805406

Lundgren, K., Kuklane, K., Gao, C., & Holmér, I. (2013). Effects of Heat Stress on Working Populations when Facing Climate Change. *Industrial Health*, *51*(1), 3–15. https://doi.org/10.2486/indhealth.2012-0089

Mansour, S. (2014). *Indoor Air Quality in Schools: An investigation of the impact of outdoor air quality, school layout, and room type*. The University of Texas at Arlington, University of Texas at Arlington, United States.

McCartney K, J., & Nicol J, F. (2002). Developing an adaptive control algorithm for {Europe}: results of the {SCATs} {Project}. *Energy and Buildings*, *34*, 623.

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

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*(4), 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

MINEDUC. (2016). OECD Review of Policies to Improve the Effectiveness of Resource Use in Schools: Country Background Report for Chile, *3*(3), 317. https://doi.org/10.1787/9789264256729-en

Ministerio del Medio Ambiente de Chile (MMA). (2015). *Declara Zona Saturada Por Material Particulado Fino Respirable Mp2,5 Como Concentración Diaria, A Las Comunas De Lota, Coronel, San Pedro De La Paz, Hualqui, Chiguayante, Concepción, Penco, Tomé, Hualpén Y Talcahuano*. Https://Doi.Org/10.1145/1542130.1542154

Mishra, A. K., & Ramgopal, M. (2013). Field studies on human thermal comfort - An overview. *Building and Environment*, *64*, 94–106. https://doi.org/10.1016/j.buildenv.2013.02.015

Mohammadyan, M., Alizadeh-Larimi, A., Etemadinejad, S., Latif, M. T., Heibati, B., Yetilmezsoy, K., … Dadvand, P. (2017). Particulate air pollution at schools: Indoor-outdoor relationship and determinants of indoor concentrations. *Aerosol and Air Quality Research*, *17*(3), 857–864. https://doi.org/10.4209/aaqr.2016.03.0128

Montazami, A., Gaterell, M., Nicol, F., Lumley, M., & Thoua, C. (2017a). Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms. *Building and Environment*, *111*, 61–71. https://doi.org/10.1016/j.buildenv.2016.10.009

Montazami, A., Gaterell, M., Nicol, F., Lumley, M., & Thoua, C. (2017b). Impact of social background and behaviour on children's thermal comfort. *Building and Environment*, *122*, 422–434. https://doi.org/10.1016/j.buildenv.2017.06.002

Montazami, A., Gaterell, M., Nicol, F., Lumley, M., & Thoua, C. (2017c). Impact of social background and behaviour on children's thermal comfort. *Building and Environment*, *122*, 422–434. https://doi.org/10.1016/j.buildenv.2017.06.002

Mors, T., Hensen, Loomans, & Boerstra. (2011). Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Building and Environment*, *46*(12), 2454–2461. https://doi.org/10.1016/j.buildenv.2011.05.025

Mors ter, S., Hensen, J. L. M., Loomans, M. G. L. C., & Boerstra, A. C. (2011). Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Building and Environment*, *46*(12), 2454–2461. https://doi.org/10.1016/j.buildenv.2011.05.025

Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, *45*(1), 11–17. https://doi.org/10.1016/j.buildenv.2008.12.013

Nicol, F., Humphreys, M. A. (Michael A., & Roaf, S. (2012). *Adaptive thermal comfort : principles and practice*. London ; Routledge. Retrieved from https://uolibraries.on.worldcat.org/search?databaseList=638&queryString=Adaptive+Thermal+Comfort%3A+Principles+and+Practice%2C+by+Fergus+Nicol%2C+Michael+Humphreys%2C+Susan+Roaf+#/oclc/730403966

Nicol, & Humphreys. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, *34*(6), 563–572. https://doi.org/10.1016/S0378-7788(02)00006-3

Nicol, J. F., & Humphreys, M. A. (2009). New standards for comfort and energy use in buildings. *Building Research and Information*, *37*(1), 68–73. https://doi.org/10.1080/09613210802611041

Nicol, J. Fergus, Humphreys, M. A., & Olesen, B. (2004). A stochastic approach to thermal comfort - Occupant behavior and energy use in buildings. *ASHRAE Transactions*, *110 PART I*(January), 554–568.

Pagels, P., Raustorp, A., Guban, P., Fröberg, A., & Boldemann, C. (2016). Compulsory school in- and outdoors—implications for school children's physical activity and health during one academic year. *International Journal of Environmental Research and Public Health*, *13*(7). https://doi.org/10.3390/ijerph13070699

Park, J. (2015). *Are Humans Good Sensors? Using Occupants as Sensors for Indoor Environmental Quality Assessment and for Developing Thresholds that Matter*. *Carnegie Mellon University, Research Showcase CMU, 2016*.

Parsons, K. C. (Kenneth C. . (2003). *Human thermal environments : the effects of hot, moderate, and cold environments on human health, comfort, and performance* (2nd ed). London: Taylor & Francis.

Parsons, K. C. (Kenneth C. . (2014). *Human thermal environments : the effects of hot, moderate, and cold environments on human health, comfort, and performance* (Third). Taylor & Francis.

Passe, U., & Battaglia, F. (2015). *Designing spaces for natural ventilation : an architect's guide* (1st ed.). Routledge, Taylor & Francis Group.

Petersen, S., Jensen, K. L., Pedersen, A. L. S., & Rasmussen, H. S. (2016). The effect of increased classroom ventilation rate indicated by reduced CO2 concentration on the performance of schoolwork by children. *Indoor Air*, *26*(3), 366–379. https://doi.org/10.1111/ina.12210

Pierpaoli, M., & Ruello, M. (2018). Indoor Air Quality: A Bibliometric Study. *Sustainability*, *10*(11), 3830. https://doi.org/10.3390/su10113830

Qualtrics. (2005). Qualtrics. Provo, Utah, USA.

Rijal, Tuohy, Humphreys, Nicol, and S. (2012). Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings. *Architectural Science Review*, *55*(1), 1–71.

Rovelli, S., Cattaneo, A., Nuzzi, C. P., Spinazzè, A., Piazza, S., Carrer, P., & Cavallo, D. M. (2014). Airborne particulate matter in school classrooms of northern Italy. *International Journal of Environmental Research and Public Health*, *11*(2), 1398–1421. https://doi.org/10.3390/ijerph110201398

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178–205. https://doi.org/10.1016/j.enbuild.2015.07.047

Salthammer, T., Uhde, E., Schripp, T., Schieweck, A., Morawska, L., Mazaheri, M., … Kumar, P. (2016). Children's well-being at schools: Impact of climatic conditions and air pollution. *Environment International*, *94*, 196–210. https://doi.org/10.1016/j.envint.2016.05.009

Santamouris, M., & Wouters, P. (2006). *Building ventilation : the state of the art*. London: Earthscan.

Santiago, P., Fiszbein, A., García Jaramillo, S., & Radinger, T. (2017). *OECD Reviews of School Resources: Chile 2017*. https://doi.org/10.1787/9789264285637-en

Schiavon, S., Hoyt, T., & Piccioli, A. (2014). Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55. *Building Simulation*, *7*(4), 321–334. https://doi.org/10.1007/s12273-013-0162-3

Schweiker, M. (2016). comf: An R Package for Thermal Comfort Studies. *The R Journal*, *8*(2), 341–351. https://doi.org/10.32614/rj-2016-050

Seppanen, Fisk, and M. (1999). Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*, (9), 226–255. Retrieved from https://www.pdx.edu/green-building/sites/www.pdx.edu.green-building/files/Seppanen association between ventilation and co2.pdf

Seppänen, O., Fisk, M. (1999). Association of Ventilation Rates and CO2 Concentrations with Health and Other Responses in Commercial and Institutional Buildings. *Indoor Air*, *9*, 226–252.

Seppänen, O. (2006). *The Effect of Ventilation on Health and Other Human Responses*. Routledge. Retrieved from https://www.taylorfrancis.com/books/e/9781849770620/chapters/10.4324/9781849770620-12

Seppänen, O., Fisk, W. J., & Lei, Q. H. (2005). Ventilation and performance in office work. *Indoor Air*, *16*(1), 28–36. https://doi.org/10.1111/j.1600-0668.2005.00394.x

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

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004). 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

Smedje, G., & Norbäck, D. (2000). New Ventilation Systems at Select Schools in Sweden—Effects on Asthma and Exposure. *Archives of Environmental Health*, *55*(1), 18–25. https://doi.org/10.1080/00039890009603380

Soto, J., Trebilcock, M., & Pérez, A. (2015). 342 : Sustainable educational buildings A proposal for changes to investment evaluation policies in Chile through the incorporation of thermal comfort and air quality criteria. In *14th International Conference on Sustainable Energy Technologies* (pp. 1–10). Nottingham.

Spengler, J. D., McCarthy, J. F., & Samet, J. M. (2001). *Indoor air quality handbook*. McGraw-Hill.

Teli, D. (2013). *Thermal performance and occupant comfort in naturally ventilated UK junior schools outside the heating season*. University of Southampton.

Teli, D., James, P. A. B., & Jentsch, M. F. (2013). Thermal comfort in naturally ventilated primary school classrooms. *Building Research and Information*, *41*(3), 301–316. https://doi.org/10.1080/09613218.2013.773493

Teli, D., James, P. A. B., & Jentsch, M. F. (2015). Investigating the principal adaptive comfort relationships for young children. *Building Research and Information*, *43*(3), 371–382. https://doi.org/10.1080/09613218.2015.998951

Teli, D., Jentsch, M. F., & James, P. A. B. (2012). Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings*, *53*, 166–182. https://doi.org/10.1016/j.enbuild.2012.06.022

Teli, D., Jentsch, M. F., James, P. A. B., & Bahaj, A. S. (2012). Field study on thermal comfort in a UK primary school. *7th Windsor Conference*, *7730*(April), 12–15.

Toftum, J., & Ole Fanger, P. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, *34*(6), 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8

Trebilcock, M., Bobadilla, A., Piderit, B., Figueroa, R., Muñoz, C., Sanchez, R., … Hernández, J. (2012). Environmental Performance of Schools in Areas of Cultural Sensitivity. *PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an Environmentally Responsible Architecture*, (November), 7–12.

Trebilcock, M., Piderit, B., Diaz, M., Hatt, T., Figueroa, R., Besser, D., … Arriagada, R. (2013). Parametric Analysis of School Classroom Typologies ' Energy Performance. *PLEA2013 - 29th Conference, Sustainable Architecture for a Renewable Future*, (September).

Trebilcock, M., Piderit, B., Soto, J., & Figueroa, R. (2016). A parametric analysis of simple passive strategies for improving thermal performance of school classrooms in Chile. *Architectural Science Review*, *8628*(March), 1–15. https://doi.org/10.1080/00038628.2016.1150251

Trebilcock, M., Soto-Muñoz, J., Yañez, M., & Figueroa-San Martin, R. (2017a). The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. *Building and Environment*, *114*, 455–469. https://doi.org/10.1016/j.buildenv.2016.12.036

Trebilcock, M., Soto-Muñoz, J., Yañez, M., & Figueroa-San Martin, R. (2017b). The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. *Building and Environment*, *114*, 455–469. https://doi.org/10.1016/j.buildenv.2016.12.036

Trebilcock, M., Soto, J., & Figueroa, R. (2012). Thermal comfort in primary schools : a field study in Chile. *Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World Cumberland Lodge, Windsor, UK, 10-13 April 2014*, (April 2014), 10–13.

Turunen, M., Toyinbo, O., Putus, T., Nevalainen, A., Shaughnessy, R., & Haverinen-shaughnessy, U. (2014). International Journal of Hygiene and Indoor environmental quality in school buildings , and the health and wellbeing of students, *217*, 733–739.

US EPA. (n.d.). Introduction to Indoor Air Quality. Retrieved June 8, 2019, from https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality

Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: Comfort for all? *Indoor Air*, *18*(3), 182–201. https://doi.org/10.1111/j.1600-0668.2007.00516.x

Van Kann, D., De Vries, S., Schipperijn, J., De Vries, N., Jansen, M., & Kremers, S. (2016). Schoolyard characteristics, physical activity, and sedentary behavior: Combining gps and accelerometry. *Journal of School Health, 86*(12), 913-921. doi:10.1111/josh.12459

van Maanen, L., van der Mijn, R., van Beurden, M. H. P. H., Roijendijk, L. M. M., Kingma, B. R. M., Miletić, S., & van Rijn, H. (2019). Core body temperature speeds up temporal processing and choice behavior under deadlines. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-46073-3

Wargocki, P., & Da Silva, N. A. F. (2015). Use of visual CO2 feedback as a retrofit solution for improving classroom air quality. *Indoor Air*, *25*(1), 105–114. https://doi.org/10.1111/ina.12119

Wargocki, Pawel, & Wyon, D. P. (2006). Effects of HVAC on student performance. *ASHRAE Journal*, *48*(10), 22–28.

Wargocki, Pawel, & Wyon, D. P. (2007). The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children. *HVAC&R Research*, *13*(March 2007), 165–191. https://doi.org/10.1080/10789669.2007.10390950

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

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

Wargocki, Pawel, & Wyon, D. P. (2016). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment*, *112*, 2–9. https://doi.org/10.1016/j.buildenv.2016.11.020

Wargocki, Pawel, Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air*, *10*(4), 222–236. https://doi.org/10.1034/j.1600-0668.2000.010004222.x

WHO. (2005). Air Quality Guidelines - Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. *World Health Organization*, (4), 1–483.

WHO. (2010). WHO Guidelines for indoor air quality, selected pollutants. *World Health Organization*, *2*(1), 1–444. https://doi.org/10.1177/156482658000200103

Willem, H. C. (2006). *Thermal and indoor air quality effects on physiological responses, perception and performance of tropically acclimatized people*. National University of Singapore.

World Health Organization, & WHO Regional Office for Europe. (2010). WHO guidelines for indoor air quality. *Nutrition Journal*, 484. https://doi.org/10.1186/2041-1480-2-S2-I1

Yun, G. Y., & Steemers, K. (2007). Time-dependent occupant behaviour models of window control in summer. *Building and Environment*, *43*(9), 1471–1482. https://doi.org/10.1016/j.buildenv.2007.08.001

Zeiler, W., & Boxem, G. (2009). Effects of thermal activated building systems in schools on thermal comfort in winter. *Building and Environment*, *44*(11), 2308–2317. https://doi.org/10.1016/j.buildenv.2009.05.005

Zhang, F., & de Dear, R. (2017). University students' cognitive performance under temperature cycles induced by direct load control events. *Indoor Air*, *27*(1), 78–93. https://doi.org/10.1111/ina.12296

Zomorodian, Z. S., Tahsildoost, M., & Hafezi, M. (2016a). Thermal comfort in educational buildings: A review article. *Renewable and Sustainable Energy Reviews*, *59*, 895–906. https://doi.org/10.1016/j.rser.2016.01.033

Zomorodian, Z. S., Tahsildoost, M., & Hafezi, M. (2016b). Thermal comfort in educational buildings: A review article. *Renewable and Sustainable Energy Reviews*, *59*, 895–906. https://doi.org/10.1016/j.rser.2016.01.033