Getting Older and Getting Colder

The Impacts of Temperature on Health and Comfort

by

Ernesto Fonseca

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2013 by the
Graduate Supervisory Committee:

Harvey Bryan, Chair
Kimberly Shea
Sherry Ahrentzen

ARIZONA STATE UNIVERSITY

May 2013

ABSTRACT

Research has demonstrated that temperature and relative humidity substantially influence overall perceptions of indoor air quality (Fang, Clausen, & Fanger, 1998). This finding places temperature quality as a high priority, especially for vulnerable adults over 60. Temperature extremes and fluctuation, as well as the perception of those conditions, affect physical performance, thermal comfort and health of older adults (Chatonnet & Cabanac, 1965, pp. 185-6; Fumiharu, Watanabe, Park, Shephard, & Aoyagi, 2005; Heijs & Stringer, 1988). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Organization for Standardization (ISO) have developed thermal-comfort standards for working-age, healthy individuals. None of these standards address the physiological and psychological needs of older adults (ASHRAE Standard 55, 2010; ISO-7730, 2005).

This dissertation investigates the impacts of thermal conditions on self-reported health and perceived comfort for older adults, hypothesizing that warmer and more-table indoor thermal conditions will increase the health and perceived comfort of these adults. To this end, a new set of thermal comfort metrics was designed and tested to address the thermal preferences of older adults. The SENIOR COMFORT Metrics 2013 outlined new thresholds for optimal indoor high and low temperatures and set limits on thermal variability over time based on the ASHRAE-55 2010 model.

This study was conducted at Sunnyslope Manor, a multi-unit, public-housing complex in the North Phoenix. Nearly 60% (76 of 118) of the residents (aged 62–82) were interviewed using a 110-question, self-reporting survey in 73 apartment units. A total of 40 questions and 20 sub-questions addressing perceptions of comfort, pain, sleep patterns, injuries, and mood were extracted from this larger health condition survey to assess health and thermal comfort. Indoor environmental thermal measurements included temperature in three locations: kitchen, living area, and bedroom and data were recorded every 15 minutes over 5 full days and 448 points. Study results start to indicate that older adults for Sunnyslope Manor preferred temperatures between 76 and 82.5 degrees Fahrenheit and that lower temperatures as outlined by ASHRAE-55 2010 increases the rate of injuries and mood changes in older adults among other findings.

DEDICATION

Con todo el amor del mundo, dedico esta disertación a mis hijos, Emma Copitzi y Emiliano Skyler quienes casi a diario me preguntaban; Papa, ¿Cuándo vas a terminar tu disertación? Y a mí querida esposa y compañera Susan, por su cariño, paciencia y apoyo incondicional para poder completar este doctorado.

A mis padres, hermanos y hermana, quien al igual que mis hijos, siempre me decían ¿Cuándo terminas, y cuando terminas?, Toda mi familia siempre ha sido mi inspiración y mi razón de ser… ¡Gracias!

ACKNOWLEDGMENTS

I would like to acknowledge my committee chair, Dr. Harvey Bryan who, since I arrived at ASU in 2004, has been an unfailingly positive influence in my academic and professional life. His expertise in building sciences established the foundation for much of the technical knowledge that sparked my research.

I would also like to thank my committee advisor, mentor, and friend, Dr. Sherry Ahrentzen, who always believed in me and pushed me for excellence. Her guidance, advice, and support as well as her dedication to my professional development and this study were fundamental to its completion. Thank you, Sherry! I would like to thank Dr. Kimberly Shea, who was always ready to advise me, to meet me in Tucson, and to and help me assess my research findings.

I would also like to acknowledge Dr. Mark Wolf for meeting with me endless times to advise me on statistical sciences and analysis; I learned much from him. And I would like to thank Dr. Liza Hita for her constant support and research recommendations, which made a great difference in making progress in my study.

With the deepest gratitude, I would like to acknowledge my loving and caring family, my daughter Emma and my son Emiliano who kept insisting that I must finish my dissertation so I could be a doctor and then play with them and, finally, my spouse, partner, and friend Susan, for her patience, support, and for always, always believing in me.

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INTRODUCTION

Problem Statement and Research Need

Although indoor environmental conditions are relatively easy to measure, their effects upon health can be difficult to assess. Agreeing upon the actual measurements to record has been a point of contention among researchers. For example, finding the link between cancer and formaldehyde leaching from kitchen and bathroom cabinetry over time is extremely difficult, as its effects can take decades to manifest in health conditions. Temperature changes, on the other hand, immediately impact activity levels, environmental sensations, perceptions, and comfort. All these indoor thermal attributes affect our health and ability to perform psychological and physiological activities (McGeehin & Mirabelli, 2001). The ability to thermoregulate (balance your physical core-body temperature) diminishes with age and high and low temperatures, as well as constant changes of indoor environmental conditions, affect thermoregulation (Havenith, 2001). This imbalance is due, in part, because physical-activity levels decrease with age (Havenith, 2001). Moreover, there is a delayed thermal sensation to cold temperatures related to older adults' inability to regulate their body temperatures as efficiently as younger adults (Tochihara, Tadakatsu, Nagai, Tokuda, & Kawashima, 1993).

A British National Survey reported that at least 10% of adults aged 65 and older measured core-body temperatures of 95.9°F, slightly lower than that of younger adults (Woodward & Exton Smith, 1973). These differences are even more evident between genders. Older men, for example, are more susceptible to cold temperatures than women; the mortality rate during cold spells is greater among older males compared to similarly aged females (Schneider & Macey, 2003).

Trans World News estimated that the average person spends 85 to 90% of their time indoors (TransWorldNews, 2010). This information has also been reported by many other journals and institutions, including the American Physical Society, which states that Americans spend 90% of their time (21 hours per day) indoors either working, living, shopping, or entertaining (Crabtree et al., 2008, p. 53). For older adults, time allocation and the space in which that time is spent is tied more strictly to income and employment than to age; consequently, their capacity to spend time entertaining or going out depends upon that income (Krantz-Kent & Stewart, 2007). According to Krantz-Kent and Stewart (2007, p. 53), writer and researcher George Godbay also found that “older persons spend less time doing paid work, more time engaging in leisure activities, more time doing house work and more time sleeping compared to younger individuals.” Older adults likely spend more time inside their own housing units, making their indoor thermal environment even more important.

The ISO and ASHRAE have developed recommendations to address thermal conditions within working spaces. These recommended standards focus upon indoor working areas, such as office or retail space, and only consider healthy working-age individuals (ASHRAE Standard 55, 2010). The objectives of my study were not to discredit ISO or ASHRAE, but to use their standards as baseline values for examining acceptable thermal-comfort standards in terms of thermal preferences of older adults in residential settings. The literature indicates that differences between older adults' thermal preferences and those of working-age individuals are clear, as seen in the literature review (McGeehin & Mirabelli, 2001). These differences reflect older adults' preferences for higher and more-stable indoor temperatures, which may reflect age changes and the amount of time spent in their own homes. In addition, aging adults experience physiological changes that reduce their capacity to thermoregulate their core-body temperature.

Despite these differences, the regulating organizations that develop standardized parameters for indoor environmental quality, including healthy thermal minimum and maximum thresholds, have not focused upon sensitive populations such as older adults, the disabled, or children. This lack of attention may have occurred because they do not represent important economic subgroupings, as large proportions of these groups are retired, unemployed, or too young to work.

Furthermore, neither major standard, ASHRAE-55 2010 or ISO 7730 2005, addresses thermal comfort and ergonomics of the thermal environment in relation to indoor environmental perceptions or specific effects on health. These standards dictate parameters and thresholds for indoor thermal comfort for all residential, commercial, office, and other nonindustrial spaces; ASHRAE and ISO standards, in accordance with each other, focus upon "thermal comfort" and more specifically upon healthy and working-age populations, with little information on health-related issues due to thermal conditions. ASHRAE's standard defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE Standard 55, 2010, p. 4). This standard incorporates the Fanger's Predicted Mean Vote (PMV) Model's seven variables in assessing such thermal comfort. Using those variables, ASHRAE developed a comfort scale assigning values from -3 to +3 to cold-to-hot sensations to define comfort and quantify thermal sensation.

Neither standard mentions thermal conditions and health implications for any demographic groups, including older adults. None of these parameters meet the profile of older populations, especially those over 65. Often at that age, health and cognitive abilities begin to decline; illnesses can be part of their daily lives. Poor thermal conditions may deter healthy living or accelerate health declines.

The need for comprehensive standards that address the thermal needs and conditions for older adults at different ages is important. A lack of action could result in less-active and less-healthy older adults and, consequently, higher healthcare costs for seniors and for our healthcare system in general. These impacts are in addition to other obvious effects, such as less-comfortable indoor conditions where spaces can be too cold, too warm, or experiencing too much thermal variability.

Significance of Research and Objectives

The links among thermal conditions, perceptions, comfort and, especially, health, have been studied in a wide variety of research projects, yet findings remain fragmented and disconnected. Turnquist and Volmer (1986) found an optimal indoor temperature for older adults of 77.54°F; slightly higher than the 76°F that ASHRAE-55 2010 recommended for the summer season. Other researchers conducting physiological studies have found that older adults have a 2–4°F lower mean oral body temperature in relation to the standardized 98.6°F, which is considered normal (Gomolin, Aung, Wolf-Klein, & Auerbach, 2005). ASHRAE acknowledges the limitations of their Standard-55, (see Chapter 2).

In addition to the failure of established standards to address the needs of vulnerable populations, technology tends to be portrayed as a simple solution for supplying comfortable indoor conditions for older adults. Certainly, technology can help regulate their indoor environments, however, technology can also impede adults with limitations. Technological advancements need to follow standards such as those of ASHARAE-55 2010, but offer a focus on older adults. George Havenith advocated for better standards or temperature predictors for older adults, partially so that more-accurate indoor thermal recommendations can be designed or established for dwelling units occupied by older adults (Havenith, 2001). Havenith also argued that making indoor environments thermally optimal could prove counter-productive; overprotecting and keeping older adults in a perfect thermal bubble might make them more prone to temperature-related illness.

As Turnquist and Volmer (1986) argued, older adults prefer slightly higher temperatures. However, extreme warm temperatures could even prove fatal, as countered by Basu and Samet (2002):

> The elderly and children may not be able to thermoregulate efficiently because of their higher sweating thresholds, thus increasing the risk of life threatening consequences when their body temperatures rise… and housing characteristics and behaviors specific to the elderly, including

> living alone, living on higher floors of apartment buildings, lacking air conditioning, and keeping windows and doors closed for safety reasons, may also increase mortality risk from heat exposure. Approaches are needed for assessing unsafe levels of heat exposure and their determinants. (p. 1219)

Many researchers (including Mackenbach, Borst, and Schols) agreed with Basu and Samet and cited excessive heat as a fatal risk. However, most researchers focused their studies on thermal comfort and the ability of older adults to thermoregulate and not on mortality and other more-severe outcomes. A few addressed the perception

of control, humidity, and thermal conditions as elements affecting thermal comfort (Fang, Clausen, & Fanger, 1998). Furthermore, perceptions have begun to be more prevalent in assessing indoor thermal comfort. Ultimately, Novieto, and Zhang (2010) cited thermal comfort as one of the most important factors for well-being in older adults.

Developing recommendations to design or retrofit housing units—or to manufacture new mechanical systems—that provide adequate indoor thermal conditions for older adults is important, and it is crucial to develop systems that can sustain stable indoor temperatures and relative humidity. With millions of baby boomers coming of age, failing to address these concerns could create an enormous public-health issue. In 2002, Howard Frumkin characterized the heat-island effect as a public-health threat, stating:

> Heat is of concern because it is a health hazard. Relative benign disorders include heat syncope, or fainting; heat edema, or swelling, usually of dependent parts such as legs…heat cramps are painful muscle spasms that occur after strenuous exertion in a hot environment. Heat exhaustion is a more severe acute illness that may cause nausea, vomiting, weakness, and mental status changes. The most serious of the acute heat-related conditions is heat stroke, which represents body failure

> to dissipate heat. The core body temperature may exceed 104 degrees Fahrenheit, muscle breakdown occurs, and renal failure and other profound physiological derangements may follow. The fatal rate is high. (p. 207).

Frumkin's heat-related hazards are issues that anyone affected by heat (indoors or outdoors) can experience, regardless of location. He mentioned that one of the most serious health threats is heat stroke, where an individual's body fails to dissipate heat. Heat stroke is of particular concern for older adults who have higher sweating thresholds and lower thermoregulating efficiencies (Basu & Samet, 2002; Gomolin, Aung,

Wolf-Klein, & Auerbach, 2005; Havenith, 2001). In addition, older adults tend to be more conservative in expending resources such as energy and money, which can limit their willingness and/or ability to pay for cooling or heating their indoor environments adequately and safely. This mental attitude could represent a problem for their well-being under extreme thermal conditions, as was the case in 1995 when a heat wave in Chicago killed 521 people; over 87% of the fatalities were individuals over 55 years old.

Currently, the US population is 307 million people, including ~40 million that are 65 or older. This older population is expected to increase to 55 million by 2020, substantially expanding the need for quality, healthy, and comfortable housing for this demographic group (US Census Bureau, 2009; Administration on Aging, 2009). Our society will need to renovate or build millions of homes and thousands of multi-unit housing complexes to meet demand.

> This housing need is reiterated by the AARP Public Policy Institute, which has stated that: many adults, as they age and their abilities change, find that shortcomings in their homes and communities can limit where they are able to live. Some of these limitations are related to features of housing stock itself, while others are rooted in community characteristics that do not accommodate an aging population. (Wardrip, 2010, p. 1)

Quality housing for older adults, as the AARP Public Policy Institute documented, includes a wide variety of rehabilitative items, including: physical adaptations, doors, bathroom accessibility, grand bars, weatherization, and location. "Through its impacts on overall cost and comfort, weatherizing a home can make the prospect of aging in place more likely for older adults with limited incomes" (Wardrip, 2010, p. 3).

These recommendations represent an opportunity to develop standards that meet the needs and preferences of older adults, to enable these individuals to thrive physically and emotionally. The development of standardized and customized standards for indoor thermal comfort for all different age groups needs to be a priority for developers of standards. My primary objective will be to align thermal preferences of older adults' with indoor thermal conditions.

Terms and Definitions

I developed the following terms and definitions, based upon current literature and research, to standardize and operationalize the meaning of all terms for the reader. Some definitions are the result of literature research and others are well established and well-known within the sciences of physics and mechanical engineering.

Activity: Daily actions and biological energy associated with the actions that an individual requires to perform a given task, including resting and sleeping

Asymmetry: Cooling or warming of the human body due to cold or warm surfaces, items, or building surfaces

Draught: Local cooling of the body caused by air movement

HVAC Controls: Manipulation that home residents exercise within their indoor environment to adjust their indoor temperature at any given moment

Humidity Ratio: Amount of water vapor contained in dry air in a given volume

Metabolic Rate: Transformation of chemical body energy into heat and mechanical work by metabolic activities within an organism (ASHRAE-55 2010)

Maximum Temperatures: Highest temperature recorded in a given space over a given time

Minimum Temperatures: Lowest temperatures recorded in a given space over a given time

Mood: Conscious state of mind or predominant emotion or feeling

Muscular and Joint Pain: Physical suffering associated with bodily disorder (disease or an injury); a basic bodily sensation induced by a noxious stimulus, received by naked nerve endings, characterized by physical discomfort (pricking, throbbing, aching), and typically leading to evasive action

Operative Temperature: Ideal temperature needed to function within a given space

Perception of Thermal Comfort: Idea and reaction of an individual to thermal conditions. McIntyre stated that “a person’s reaction to a temperature, which is less than perfect, will depend very much on his expectations, personality, and what else he or she is doing at the time.” (McIntyre, 1980)

Physical Injuries: Physical damage produced by the transfer of energy (kinetic, thermal, chemical, electrical, or radiant) or by the absence of oxygen or heat; the interval of time over which the energy transfer or the deprivation of physiological essentials occurs is known as “exposure,” which may be acute or chronic (National Center for Health Statistics, 1998; Hyattsville, MD, Public Health Service, 1998)

Sleep Patterns: State of decreased awareness of environmental stimuli distinguished from states such as coma or hibernation by its relatively rapid reversibility; sleeping individuals move little and tend to adopt stereotypic postures; also relates to the different sleeping schedules measured by their duration, quality, and placement over 24 hours

Temperature Variability: Temperature changes within an indoor residential environment over a given time

Thermal Comfort: Condition of mind that expresses satisfaction with the thermal environment (ASHRAE-55 2010)

Thermal Neutrality: Condition in which an individual is neither warm nor cold

Thermoregulation: Biological and chemical reaction to maintain body basal/core temperatures within comfortable and healthy ranges

Window Opening: Manipulation that home residents exercise within their indoor environment to open and close windows to adjust thermal conditions at any given time

Chapter 2

LITERATURE AND THEORETICAL REVIEW OF THERMAL COMFORT

My study seeks to better understand the impacts of temperature and temperature variations upon thermal comfort, perception, and health. Consequently, I propose an alternative set of metrics to the traditional ASHRAE-55 2010 Standards, which I name the SENIOR Comfort Metrics. I will test both metrics to see which system better predicts the impact of temperatures on comfort, perception, and health. In order to support my methodology and statistical tests, I reviewed existing research on thermal comfort and current standards. The following review is a compilation of most relevant information in thermal comfort and its standardization industry.

Theoretical Framework

This study builds upon two theories in the field: the Traditional Thermal Comfort Theory developed by Danish researcher Povl Olev Fanger in the 1960s and the Adaptive Theory, which resulted from a collaborative effort of investigators around the world and has been progressing for several decades. The most prominent supporters of this latter theory include Gail Brager, Richard de Dear, Fergus Nicol, and Michael Humphreys. Together, these two theories revolutionized thermal-comfort conceptualization and strategies.

1. The Thermal Comfort Theory: In his theory, Fanger defined an individual's thermal comfort as "the condition in which the subject would prefer neither warmer nor cooler surroundings. Thus thermal neutrality is a necessary

condition for thermal comfort" (Fanger, 1970, p. 14). He argued that we must find the optimal temperature at which people find the environment to be neither cool nor warm and concluded that thermal comfort is reached for at least 80% of all occupants in a given space.

2. The Adaptive Theory: This theory explained that, "people are not passive receivers of their thermal environment but alter or adapt to their environment to suit themselves, and if a change occurs that produces discomfort, people will tend to act to restore their comfort" (Nicol & Humphreys, 2002; deDear & Brager, 1998). Human interaction plays an active role in indoor thermal comfort through adaptive actions. These actions can include modifying activity levels, drinking cooler or warmer liquids, increasing or decreasing body insulation, or activation of mechanical building systems (e.g., fans, HVAC, opening or closing windows).

Both theories contain four deficiencies that make their approach inadequate for developing adequate thermal conditions for older adults in residential settings. This judgment does not degrade the value that both theories have provided over the years; instead, it identifies deficiencies that could be remedied to increase the thermal comfort of older adults.

The four identified deficiencies in the standard recommendations:

1. Standard recommendations (e.g., ASHRAE-55 standards or Adaptive Theory recommendations) focus exclusively upon working environments. Both

theories based their framework and recommendations on research conducted in working places; little research was conducted in residential settings.

2. Both theories and standard recommendations based their framework and recommendations on the assumption that users are: a) working-age individuals; b) between the ages of 18 and 65; and c) healthy and able to use their full physical and physiological capacities, an invalid assumption for many older adults.
3. For the most part, temperatures were analyzed in steady-state conditions, where thermal variation does not exist and fluctuations are not addressed. Many older adults cannot thermoregulate or are hypersensitive to minimal thermal changes, making indoor stable conditions a priority in actual living spaces.
4. Little research has been conducted to assess thermal comfort for adults at different ages in varying health conditions; no effort has been made to craft recommendations or standards for the thermal environments for these populations. In addition, scant research has linked perceptions, mental conditions, and psychological health conditions with actual thermal comfort.

Thermal comfort has been widely studied. Fanger developed the first comprehensive study on thermal comfort based upon research on students in 1970. His work has served as the foundation for most subsequent studies on thermal comfort. However, subsequent research explaining that "thermal comfort is the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55, 2010,

p. 4) has left many questions unanswered and gives room for too much speculation. This chapter explores the theoretical and empirical research on thermal comfort, age and temperature, and thermoregulation.

ASHRAE-55 2010

In 1966, ASHRAE published their Standard 55 for the first time. The main goals were to seek ideal thermal environments, maximize thermal comfort for as many occupants as possible, and increase workers' productivity. Since then, they have released updated standards in 1974, 1981, 1992, 2004, and the latest one in 2010, defined as "intended for use in design, commissioning, and testing of buildings and other occupied spaces and their HVAC systems and for the evaluation of thermal environments" (ASHRAE Standard 55, 2010, p. 2).

ASHRAE has been one of the most prominent developers of standards, along with the ISO. For many years, ISO has led the thermal-comfort arena, pressing for changes and searching for a more flexible and adaptable model. ASHRAE-55 2010 was brought into close agreement with ISO 7726 and 7730; they also introduced recommendations for an adaptive model. In addition to merely allowing for cooling or heating through mechanical means, these standards allow designers to consider using natural ventilation as an optional method for cooling or heating a space. Previous ASHRAE versions of this standard did not allow alternatives or changes, even small ones that were not a direct result of a computerized PMV/PPD calculation.

Fanger originally designed the PMV and PPD calculations and ISO and then ASHRAE later adopted them. The PMV/PPD indices allow mechanical designers to calculate votes for optimal thermal comfort and to determine the thermal percentage of potentially unsatisfied users for a given space under steady-state conditions.

Vote calculations refer to the equation that mechanical engineers use to determine how many individuals in a particular space will or will not be satisfied under specific thermal conditions. ASHRAE-55 2010 allows for more flexibility in the mechanical

design; for example, slightly higher air speeds or temperatures are acceptable outside the limits of the thermal-comfort zone (ranges are between 69 and 81.5°F). Originally, ASHRAE minimum and maximum temperature thresholds for both winter and summer conditions were 68 and 81°F. The new ASHRAE-55 2010 standard also outlines humidity limits at 0.12 lb/H_20 per 1 lb of Dry Air; the combination of air humidity and air temperature will vary when one of those two factors changes, which makes thresholds more flexible and adaptable in some cases (Figure 1). Finally, the standard adds a basic satisfaction survey to assess thermal comfort, although this survey is used only to gather information and typically is not used to design new mechanical systems.

Survey questions include: the season in which the survey is being administered, room location, floor level, proximity to a window, clothing, body position, activity level, and how cold or warm the person feels. According to ASHRAE's descriptions, the standard's main purpose is to "specify the combination of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space" (Olesen B. W., 2004, p. 3). It defines environmental factors as air speed, temperature, and relative humidity and personal factors as activity and clothing. ASHRAE also defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55, 2010, p. 4).

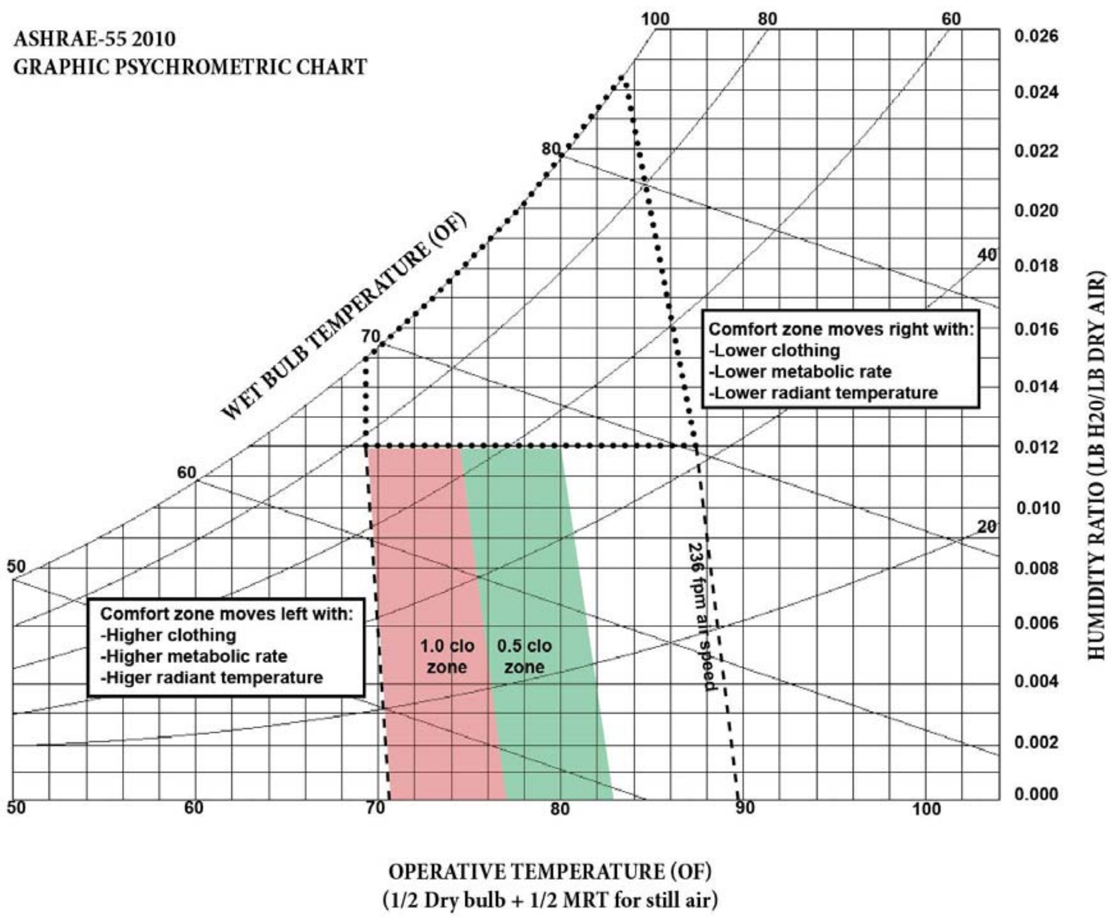

Figure 1. ASHRAE-55 2010 Psychrometric chart for each value per combination.

This organization and its technical committees acknowledged that, given the myriad of physical and psychological variables from person to person, it is impossible to reach a satisfactory thermal-comfort zone for everyone. Nonetheless, the ASRAHE technical committee outlined six factors that, according to their research, affect thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. "These conditions are needed for a person's thermoregulatory system to maintain a reasonable constant internal temperature. For a given activity level, skin temperature and sweat secretion are seen to be the only physiological variables influencing the heat balance" (Fanger, 1970, p. 37).

ASHRAE understands that these indoor environmental factors will change over the course of the day; therefore their calculations apply only under steady-state conditions. In 1966, ASHRAE-55 published a thermal-sensation scale to assess thermal preferences; these preferences were later referred to as thermal comfort. It was a seven-point scale that ranged from -3 to +3 and was applied via a simple survey that asked occupants to assess comfort levels using the following rating system: -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, and +3 hot. Fanger used this scale to conceptualize perfect thermal comfort as the absence of hot or cold reaching thermal neutrality, an argument that researchers such as De Dear and Brager later contested.

ASHRAE also uses the PMV model to assign thermal votes and determine the percentage of individuals who do not feel thermally comfortable in an environment (ASHRAE Standard 55, 2010, p. 5). Another measure that ASHRAE takes into account to determine thermal satisfaction is cycling variations where temperatures rise and fall within a time period, also known as temperature variations; for this measure, ASHRAE outlines acceptable thresholds of temperature variations (Table 1). The limits on thermal variability do not represent temperature in terms of highs and lows but instead the amount of degrees that an indoor temperature can vary in a given period of time. For example, ASHARE-55 2010 allows for a maximum of 4°F increases or decreases in gradual indoor temperature within one hour, or 2°F change in 15 minutes.

Table 1
ASHRAE-55 2010 Limits on Thermal Variability

Time Period in hours	0.25	0.5	1	2	4
Max Temperature in °F	2.0	3.0	4.0	5.0	6.0

Discussion and Conclusions

ASHRAE has advanced mechanical engineering for heating, refrigeration, and air conditioning since 1896. With over 50,000 members and many highly qualified technical committees, they are dedicated to providing continuing education, performing research, and publishing documents every year in journals, standards, technical books, and other publications. Although they have undoubtedly advanced the science of heating and refrigerating, in the realm of indoor environments and thermal comfort, their focus has been on working environments and working-age individuals.

This approach has virtually ignored all residential environments, leaving no standard that determines optimal conditions for those settings. The standards have assumed that residents have absolute control of indoor climatic conditions. Although most residents in the US do control their thermostats, in some residential settings a centralized HVAV limits and controls such access. Access to a thermostat does not guarantee high-quality indoor temperature or even adequate thermal comfort. Perhaps the most important limitation that homeowners face is their inability to influence the mechanical design of the properties they occupy. Most HVAC design is either oversized or undersized—cooling or heating a particular space too quickly or too slowly. Most of these limitations are due to a lack of direction from standard and specification developers. Not customizing standards to indoor thermal conditions has created a vacuum in the scientific-knowledge base regarding the thermal needs of vulnerable populations, particularly of older adults and children. It is understandably difficult to design for residences, considering the many variables of human behavior and. while this problem originates from our thermal needs, it goes beyond those needs and affects how we regulate construction, materials selection, insulation values, HVAC design, and other building components or fixtures. These residential attributes, including mechanical systems, will determine how a building behaves thermally, which, in turn, will affect indoor thermal conditions. Consequently, residential users have minimal control over these attributes and, in many cases, if their indoor conditions are extreme, they are unable to offset these extremes through mechanical means, which may prove costly.

According to the ASHRAE-55 2010 Standard, thermal operating parameters of 69–81.5°F, as well as its thermal variability parameters, have been tested in working environments with healthy, working-age individuals and seem to satisfy at least 80% of that population. The literature indicates, however, that these individuals can thermoregulate more efficiently than older adults. Older adults may have problems regulating their body temperatures in spaces with constant thermal variability. In addition to not regulating their internal body temperatures as well as younger adults, their skin experiences a delayed thermal sensation (Basu & Samet, 2002). When temperatures increase or decrease, they do not register such temperature changes until later. Under extreme conditions, this delay can induce hypothermia or hyperthermia.

ISO Standards

The ISO is the world's largest developer and publisher of International Standards. Established in February1947, ISO comprises a network of the national standards institutes from 162 countries, with one member per country coordinating the system from a Central Secretariat in Geneva, Switzerland. This nongovernmental organization bridges public and private sectors; many of its member institutes are part of the governmental structure of their countries or mandated by their government, while other members have affiliations in the private sector, having been established by national partnerships of industry associations. With these various connections, the ISO enables a consensus on solutions that meet both the requirements of industry and the broader needs of society (ISO, 2011).

ISO-7730 and ISO-14415

The ISO developed a series of standards that address the thermal environments to which humans are exposed. ISO-7730 is one of the standards developed parallel to ASHRAE-55. ISO performed most of the scientific test and technical specifications; ASHRAE developed the standard manual that articulates rules and regulations that designers and engineers use to design of indoor thermal environments. ASHRAE has developed multiple standards, differentiated by a numbering system. In this case, the standard addressing indoor thermal environments is ASHRAE Standard 55 or ASHRAE-55. The ISO uses a similar system to organize their standards.

ISO-7730 begins by describing human thermal sensation: "A human being's thermal sensation is mainly related to the thermal balance of his or her body as a whole. This balance is influenced by physical activity and clothing" (ISO-7730, 2005, p. v). Just as ASHRAE does with Standard 55, ISO-7730 uses the PMV-PPD indices to provide percentage information on thermal discomfort and user dissatisfaction. The ISO also identifies the most common causes of thermal discomfort cause by undesired cooling or heating of the body. "The most common local discomfort factors are radiant temperature asymmetry, draught, vertical air temperature differences, and cold or warm floors"
(ISO 7730, 2005, p. v).

The goal of ISO-7730 is to determine thermal comfort using the PMV and PPD calculations. It explicitly states, "this standard is applicable to healthy men and women exposed to indoor environments where thermal comfort is desirable, but where moderate deviations from thermal comfort occur, and in the design of new environments or the assessment of existing ones" (ISO-7730, 2005, p. 1).

ISO-7730 used the PMV index to calculate thermal-comfort conditions.
This index was designed to derive such calculations under steady-state conditions that assumed that indoor environments are completely stable and temperatures do not change. This state is virtually impossible even under the most-controlled conditions, as

ISO-7730 indicated: “The method in their own standard 7730 to assess thermal comfort is based on steady-state conditions. The thermal environment is, however, often in a non-steady-state and the question arises as to whether the methods then apply” (ISO-7730, 2005, p. 11). Nonetheless, the ISO asserted that the PMV index can be applied with relatively accuracy during minor fluctuations of <1°F between peak temperatures; higher-peak variations will decrease comfort. ISO expressed that, although this standard was developed for the work environment to predict the thermal comfort of healthy working-age individuals, researchers need to further develop and standardize the PMV-PPD model application to reach its full potential.

To advance the potential of the PMV-PPD indices, ISO-14415 was developed in 2005; it added variables to assess thermal comfort for people with special needs: sensory impairment and paralysis, difference in body shape, impairment of sweat secretion, differences in metabolic rate, and influence of thermal stress on other physiological functions. The updated standard followed the same protocol as ISO-7730 and used the PMV index to determine thermal comfort. The standard continues to undergo review and testing, with the understanding that: “thermal conditions that are normally considered as moderate and provide thermal comfort may not be moderate or acceptable to people with disabilities” (ISO-14415, 2005, p. 3).

For the first time, a standardization organization attempted to address the needs of individuals in poor health or who may be pregnant, aged, or disabled. However, the ISO also explained that “the PMV and PPD indices are statistically derived from the theoretical comfort equation and experimental data from a larger number of subjects, mainly young adults and some older persons were considered, but generally the aged were not" (ISO-14415, 2005, p. 3). Therefore, the method to predict thermal comfort suggested by ISO-7730 may be inadequate for older populations that suffer from thermoregulatory impairments. The same dilemma applies for persons with physical disabilities. For example, "individuals with spinal cord injury also have vasoconstriction disorders and impaired sweating capacities, hence their thermoregulatory systems do not compensate well during thermal changes" (ISO-14415, 2005, p. 3). Even when older adults age in a relatively healthy manner, thermoregulation can be a serious thermal stressor:

> Shifts of thermal circadian rhythms are often found among healthy aged persons. Vasoconstriction against cold environments, as well as vasodilatation and seat secretion against hot environments, is weaker and starts later in an aged person. Thermal sensation becomes dulled and many cases of spontaneous hypothermia in the elderly are reported. (ISO-14415, 2005, p. 8)

Although these individuals are relatively healthy, their cardiac functions still change at different times during the day, distributing more or less blood through their circulatory systems, creating or dissipating heat while setting thermal-comfort levels.

The Predicted Mean Vote (PMV) Index

The PMV index predicts the mean value of the votes of a large group of individuals on a seven-point scale (Table 2), based on the body's heat balance. Balance is obtained

Table 2
PMV Thermal Sensation Scale

+3	+2	+1	0	-1	-2	-3
hot	warm	slightly warm	neutral	slightly cool	cool	cold

when internal heat production is equal to the heat loss to the environment. In moderate environments, the thermoregulatory system will automatically modify skin temperature and sweat secretion to maintain a heat balance (ISO-7730, 2005, p. 2).

Although derived from steady-state thermal conditions, the PMV, according to ISO-7730, can be applied with relative accuracy during minor fluctuations. Unfortunately, most fluctuations have a range that exceeds this threshold by more than the allowable +/- 1°F variation; this variation is serious and effectively nullifies its utility. Also, while the PMV predicts the mean value of the thermal votes, it does not assess the percentage of individuals dissatisfied with the thermal environment. Typically, votes are scattered around the mean value, which does not provide specificity in predicting the percentage of persons in thermal discomfort. Consequently, the Predicted Percentage Dissatisfied index was developed to determine the perceptual value of individuals in thermal discomfort.

The Predicted Percentage Dissatisfied (PPD) Index

The PPD is an index that quantifies the predicted percentage of people who feel too cool or too warm. Thermally dissatisfied people include those who vote on the PMV index scale (see Table 3): hot, warm, cool, or cold.

Table 3
Scales of Warmth and Preference (Humphreys, Nicol, & Raja, 2007, p. 59)

Code	ASHRAE	Bedford	McIntyre	Nicol
3	Hot	Much too warm		
2	Warm	Too warm		Prefer much cooler
1	Slightly Warm	Comfortably warm	Prefer cooler	Prefer a bit cooler
0	Neutral	Comfortable	No change	No change
-1	Slightly cool	Comfortably cool	Prefer warmer	Prefer a bit warmer
-2	Cool	Too cool		Prefer much warmer
-3	cold	Much too cool		

In addition to this traditional scale, the PPD index also predicts the number of persons who may be dissatisfied with their thermal environment among a large group of people. The rest of the group will feel thermally neutral, slightly warm, or slightly cool (ISO-7730, 2005, p. 5). Thermal neutrality is necessary for thermal comfort but is not the only factor that determines this condition. The PMV and PPD express and predict computerized, calculated thermal conditions that can determine the parameters for body discomfort as a whole. This index merely shows optimal comfort calculated by a computer model; it does not represent actual votes of individuals on thermal comfort.

Discussion and Conclusions

The elements that define ISO-7730 and most other ISO standards are the application of the PMV-PPD indices. The main concern regarding this model is that the ISO only considered healthy working-age individuals for these calculations; as a result, this limited research precludes applying the model to the constraints under which older adults might benefit by it. The model's other basic constraints were the same as those outlined for ASHRAE-55 2010; the PMV-PPD indices were based upon steady-state conditions that are not realistically attainable, especially in a residential setting. The ISO-14415 moved in the correct direction in addressing these issues; yet this technical standard continues to use the outdated PMV-PPD model. In theory, the PMV-PPD model is useful, but it needs upgrading to include different metabolic rates of older adults and people with disabilities.

Although ISO-14415 is currently under review, its modified PMV-PPD model is the best-available approach for predicting thermal preferences for older adults and other population groups. The new equation proposed by ISO-7730 in combination with ISO-14415 is evolving in the right direction, especially as it considers health factors that affect thermal satisfaction and health, such as vasoconstriction limitations and other physical disabilities. The equation offers a partial solution to defining thermal environments that would be most effective for older adults. These indices, however, do not consider a wide range of health issues that will affect projected results, such as inability to move frequently, joint degradation, or the health declines that correspond with aging. Furthermore, the system does not account for or compute perceptual differences on thermal comfort from older adults or segments of older adults by age and gender groups.

Including these new variables as well as thermal responses from a larger population of older adults of all health conditions, age groups, and genders could allow the PMV-PPD equation and further indices to better assess and predict thermal comfort for older adults. The current rigid approach needs to allow for more flexibility and incorporate most recommendations of the adaptive-comfort model. Additionally, thermal variability is a lingering concern. Differing levels of thermal variability need to be customized for different age groups, genders, and health conditions. Incorporating this variable into the PMV-PPD equation will guide engineers and designers to predict more-suitable thermal environments for older adults.

Building a completely new model would be problematic and time-consuming; it would be more beneficial to reassess and adapt the current model. The PMV-PPD model uses correct algorithms, which could be modified and correlated to a greater sample of older adults' responses on thermal sensation and perceived and actual health outcomes. The ISO could undertake this task in the near future as they see the need for healthier indoor environments for older adults, especially as baby boomers head into retirement.

The Fanger Model

In the 1960s, Povl Ole Fanger, Danish engineer and investigator, developed the most complete thermal-comfort model and analysis. His aim was to understand the conditions needed to reach an optimal indoor thermal-comfort state. However, he acknowledged the impossibility of multiple individuals in the same room reaching that state and satisfying all present individuals at the same time. Given that scenario, he altered his aim to reach a level of thermal comfort for most individuals at any given time.

Fanger established the principles for analysis of any indoor environment (Fanger, 1970). He understood that the mechanization of buildings was becoming a solid component of all buildings constructed in Europe and the US. "The growing mechanization and industrialization of our society has resulted in most people spending by far the greater part of their lives (often more than 95%) in an artificial climate" (Fanger, 1970, p. 13). Fanger also adopted the definition of thermal comfort, established by ASHRAE and accepted today, as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 55-66, 1966).

Fanger identified six main factors that affect thermal comfort: activity level (which creates body heat); thermal resistance of clothing, or clothing insulation; air temperature; mean radiant temperature; relative air velocity; and water vapor pressure in ambient air. All of these, he asserted, affect most thermal conditions and thus thermal comfort and, through a combination of these factors, optimal comfort is achieved. "In all cases—thermal comfort—is the product that is being produced and sold to the customer by the heating and air conditioning industry" (Fanger, 1970, p. 15). Along with the heating and refrigerating industry, Fanger conceptualized thermal comfort as a product that needed to exhibit certain qualifications in order to be sold. Fanger (1970) also discussed in his book, *Thermal Comfort*, the term "thermal neutrality," the condition in which the subject does not prefer warmer or cooler indoor environments. Thermal neutrality must always be present to reach optimal thermal-comfort conditions.

The Thermal Comfort Equation and Heat Balance

Fanger developed a relatively complex equation to calculate all possible combinations of all six thermal factors. His objective was to derive the perfect combination of the six variables to reach optimal thermal comfort. Investigators around the world collected and examined preliminary field data on how people felt about their indoor temperatures. However, in many cases, the data was not reliable, as either some or most of the six variables were not measured (Fanger, 1970, p. 20).

The most important condition necessary to reach thermal comfort for any person exposed for long periods of time to any indoor environment is heat balance. Yet this one factor is insufficient to reach that optimal thermal comfort. Heat balance is a natural reaction of our bodies to thermoregulate and adapt to cold, warm, or even neutral environments. Fanger established and proposed the double-heat-balance equation, which accounts for human activity, clothing, and indoor actual conditions, as follows:

$$f(H/A_{Du}, I_{cl}, t_a, t_{mrt}, P_a, v, t_s, E_{sw}/A_{Du}) = 0$$

Where

H/A_{Du} = Internal heat production per unit body

I_{cl} = Thermal resistance of the clothing

t_a = Air temperature

t_{mrt} = Mean radiant temperature

P_a = Pressure of water vapor in ambient temperature

v = Relative air velocity

t_s = Mean skin temperature

E_{sw}/A_{Du} = Heat loss per unit body surface area by evaporation of sweat secretion

Fanger explained that the equation was designed to account for physiological variables that influence heat balance or thermoregulatio—activity and sweat secretion.

> The sensation of thermal comfort has been related to the magnitude of these two variables. Experiments involving a group of subjects at different activity levels have been performed to determine mean values of skin temperatures and sweat secretion, as functions of the activity levels for persons on thermal comfort. (Fanger, 1970, p. 22)

Other Factors in Fanger's Model

In addition to air movement, radiant and mean temperatures, and internal body heat, Fanger explained that other physiological factors affect an individual's ability to feel thermally comfortable in any indoor environment. He considered several physical and space attributes that might impact thermal sensation: age, gender, body build, menstrual cycle, ethnic differences, food, circadian rhythm, thermal transients, unilateral heating or cooling of the body, asymmetric radiant fields, draught, cold and warm floors, floors with footwear and bare feet, color, crowding, and air pressure.

When comparing older adults to college-age individuals, Fanger noted similarly neutral temperatures and only small differences in thermal-comfort preferences (1970). In agreement with ASHRAE-55 1966, he observed that adults over 40 preferred ~1.8°F higher temperatures than college-age individuals. The same was noted for women during the menstrual cycle; with temperatures varying between -0.41°F and +0.99°F.

Overweight individuals preferred slightly cooler environments, with -0.46°F difference. No significant differences were found in circadian rhythms or thermal transients for individuals exposed to hot, cold, and neutral temperatures. Lastly, no significant differences were found among ethnic groups and small differences were found when individuals ate spicy foods, which tend to increase a person's metabolic rate (Fanger, 1970, p. 92).

Fanger's conclusions contradicted other findings that indicated that age mattered, as found when Kenney, Thaney, and Gomolin observed that older adults get colder as they age and experience more difficulty regulating their core-body temperature (Gomolin, Aung, Wolf-Klein, & Auerbach, 2005; Kenney & Thaney, 2003). Although Fanger's tests were extensive, his test subjects were mostly college-age students; only a small fraction were over 55. In addition, and one of the main reasons that research into real-space thermal conditions is needed, all his tests were conducted in a climate chamber and under controlled conditions, which do not represent a real human habitat.

Fanger investigated the process of draught to better understand how the human body responds to indoor thermal conditions in different layers in a space. He defined draught as the "unwanted local convective cooling of a person, also defined as radiant cooling" (Fanger, 1970, p. 98). He noted that this condition had little effect on overall thermal comfort and influenced final sensations only. Radiant cooling (or heating) is essentially temperature changes that can be felt from cold (or hot) surfaces in any given space. The same minimal observations were found, reported Fanger, for other conditions such as cold and warm floors, floors and footwear, color, bare feet, and air pressure. Crowding, however, resulted in no changes in participants' psychological responses (Fanger, 1970, p. 104).

Discussion and Conclusions

Fanger, considered the father of thermal comfort, developed an impressive, comprehensive model to predict thermal comfort. Yet, he acknowledged that his thermal-comfort equation depended upon variables that were difficult to re-create in real life, such as steady-state conditions and sea-level atmospheric pressures. These and other variables are needed to extend Fanger's contributions, to feed scenario research under actual space and ambient conditions. Until he released his findings, which grouped together factors, researchers had focused upon isolated variables that affect thermal comfort and had not considered elements that could affect comfort, such as age, activity, or physical condition.

Despite the restrictiveness of Fanger's thermal-comfort equation, this equation was deduced from actual field data (Fanger, 1970, p. 16). Yet this equation can provide only predicted information of indoor thermal preferences—what a given majority of working-age and healthy individuals may prefer. His study lacked information on the thermal sensation of actual individuals. Geographic locations where test subjects were recruited and tested constitute another limitation that compromises the validity of his model. The human body adapts to outdoor thermal conditions and develops expectations for indoor temperatures based on these conditions. (Brager & deDear, 1998)

Fanger's sample size and choice of population for the study are additional weaknesses. The sample population did not represent vulnerable populations, such as children, older adults, or disabled individuals; nor was the testing performed during physical or physiological events for those who were injured, stressed, tired, sleeping, excited, upset, or experiencing other emotional or physical changes. The test population was concentrated in only two climates and locations, important considering variations in human climate adaptability (Yang & Zhang, 2008). Of a sample of 976 test subjects, 720 college-age individuals (50% women, 50% men) were tested in Kansas, and 128 college-age individuals and 128 older adults were tested in Denmark (Fanger, 1970, p. 77). Finally, Fanger's testing was limited because it occurred under tightly controlled conditions in climate chambers.

Although Fanger asserted that the two groups (college-age students and older adults) had a nearly identical neutral temperature, he acknowledged that no systematic experiments were performed to identify the thermal comfort of older adults. In other words, older adults were tested without baseline considerations and measurements, and only responses while in the climate chamber were factored into the equation.
For example, no questions were asked to determine if there were any factors that may alter their test responses, such as fatigue or injury. Without these considerations, Fanger determined that the difference in preferred temperatures between adults 65 and older and college-age students was 0.54°F, with older adults preferring a neutral temperature

of ~78.42°F. This finding conflicts slightly with Turnquist and Volmer's results (Turnquist & Volmer, 1986); they identified an optimal temperature for older adults of 77.54°F. Varying testing protocols, sample characteristics, or other climatic or demographic and geographic factors may explain the different results.

Despite the contrasting findings, it is generally known that older adults prefer moderately higher temperatures (Rohles, 1969, p. 1), partly because core-body temperatures decrease with age (Kenney & Munce, 2003). The major issue may not be moderately higher or lower optimal temperatures, but sudden and constant changes in temperature, which has been understudied in most research projects (Havenith, 2001; Gomolin, Aung, Wolf-Klein, & Auerbach, 2005; Novieto & Zhang, 2010). Sudden changes in temperature likely represent a more-serious issue for older adults. Glandular functions gradually decline and sweating thresholds increase with age, especially those 70 and older (Kenney & Thaney, 2003). Sudden and constant changes are impossible to calculate with the thermal-comfort equation, which was established under steady conditions rarely found in residential environments. Temperatures may be relatively stable where thermostats are located; variability likely exists in other living spaces of a given residence.

Fanger's thermal-comfort model and equation set the foundation for subsequent and current thermal-comfort studies. In fact, little has changed since he released his findings in the late 1960s. Arguably, Fanger's thermal-comfort equation and his indices of PMV and Predicted Percentage Dissatisfy (PPD), revolutionized the heating and refrigerating industry and are still used, with only minor modifications. Soon after he began his study, Fanger recognized that the pursuit of thermal comfort could not only increase human comfort, but their health as well; yet health was never his focus. Instead, he seized upon the potential impacts of greater human productivity and efficiency. I mark this focus as the beginning philosophical stance that lingers to the present day: we aim to maximize comfort in our working environments mostly to increase productivity and reduce absenteeism of employees. This perspective naturally excludes residential environments and nonworking residents, which surely was never Fanger's goal; his attention concentrated upon developing standards for working conditions and working-age individuals.

Fanger tested his subjects in climate chambers at Kansas State University and at the Technical University of Denmark. These chambers can sustain, under controlled conditions, steady indoor temperatures and relative humidity. This setting has engendered controversy, because steady thermal conditions are virtually impossible in actual indoor environments and even less likely in residential indoor settings. However, the data gathered from Fanger's climate chambers have helped us to understand preferences even when we cannot replicate those conditions. We should not take these values as absolute; we should accept them as trends that merely indicate preferences for higher or lower temperatures. Other considerations that serve compromise Fanger's numeric results are the minimal number of older adult subjects and the paucity of different age groups. He reported minimal information on medical conditions and perceptions of health and actual comfort from older adult participants.

Regardless of these limitations, Fanger's work altered the thermal-comfort theory and dramatically expanded this field of knowledge. He pioneered the study of thermal comfort and built the foundation for future research on adaptive comfort and healthy indoor environments.

The Adaptive Thermal Comfort Model

Another model that centered on thermal comfort is known as the Adaptive Thermal Comfort Model. Nicol and Humphreys argued that "people have a natural tendency to adapt to changing conditions in their environment" (Nicol & Humphreys, 2002, p. 563). They studied the adaptive approach using field studies and surveys aimed to predict comfortable temperatures and determine the combination of thermal conditions necessary to reach that comfort level (Nicol & Humphreys, 2002). The rational approach, as they called it, is based upon the laws of physics and the physiological parameters of heat transfer. "People are not passive receivers of their thermal environment but alter or adapt to the environment to suit themselves, and if change occurs that produces discomfort, people will tend to act to restore their comfort" (Yang & Zhang, 2008, p. 393). Yang and Zhang argued that humans do not remain inactive when feeling thermal discomfort; instead, they try to alter their environment. For example, they will open windows, turn on fans, close windows, or manipulate mechanical systems.

Investigators, searching for a thermal-comfort system that adapts to the needs of occupants, developed many thermal-sensation surveys; each used similar scales and some are simpler to answer. Table 3, lists four scales developed since 1930 (see Page 24).

The ASHRAE-55 2010 is the most popular thermal-sensation scale to measure thermal comfort (ASHRAE Standard 55, 2010). Nicol and Humphreys argued that with this system, the PMV and PPD indices are not ideal at assessing thermal adaptability and actual comfort.

The PMV system also requires information about clothing insulation and metabolic rates that can only be speculated upon, based on the assumed age and good health of individuals. They also empirically asserted that rational systems such as the PMV-PPD model are not as efficient at predicting thermal comfort as other, simpler systems (Nicol & Humphreys, 2002, p. 564).

In 1973, Nicol and Humphreys suggested that within indoor environments, mean temperatures among different climates do not vary as many might expect. For the most part, in moderate climates, outdoor conditions are not so crucial to the equation; instead thermal conditions between different buildings and spaces make a greater difference in terms of being comfortable or not. Furthermore, the difference is accentuated between buildings that are conditionally comfortable and those that are not, which can change the thermal expectations and comfort of users.

People have different expectations about conditioned and unconditioned types of environments (deDear & Brager, 1998). People are more apt to accept thermal conditions when they have more control of their indoor environments, whether through access to indoor mechanical systems or operable windows. Olesen and Brager argued that:

> When occupants have control over operable windows and are accustomed to conditions that are more connected to the thermal natural swings of the outdoor climate, the subjective notion of comfort and preferred temperatures change as a result of availability of control, different thermal experience, and resulting shifts in occupant perceptions or expectations. (Olesen & Brager, 2004, p. 25)

Nicol and Humphreys supported Olesen and Brager's reference to temperature variability and adaptability stating that:

> Variability is generally thought of as a bad 'bad thing' in centrally controlled buildings because occupants are adapted to a particular temperature. Much change from this and they become uncomfortable. In buildings where occupants are in control, variability may result from people adjusting conditions to suit themselves. A certain amount of variability then becomes a good thing. (Nicol & Humphreys, 2002)

Nicol and Humphreys categorized thermal-comfort standards as those "that standardize a methodology, such as the PMV-PPD calculation tools and those that define good practice. An adaptive standard will most usefully be of the latter type" (Nicol & Humphreys, 2002, p. 569). They presented evidence showing higher thermal-comfort satisfaction in buildings that can be adapted. This approach accounted for outside air temperature and not for centrally conditioned buildings. They based their equation on empirical evidence, and it is "almost" as follows (Nicol & Humphreys, 2002, p. 569):

$$T_C = (56.30) + (0.37 * T_O)$$

Where, T_C = Comfort temperature and T_O = Monthly outdoor mean temperature

Factors that Affect Comfort and the Adaptive Process

According to Brager and deDear, "In contemporary thermal-comfort research there appears to be an irreconcilable split between heat balance and adaptive modeling approaches, heat balance models, also refer as 'static' or 'constancy' models" (Brager & deDear, 1998, p. 83). Brager and deDear's argued that existing standards are based upon the heat-balance model, which is predicted using the PMV-PPD indices and that these are, at the same time, based upon static thermal conditions for centralized air-conditioned buildings. The principles and standards based on the existing standards have been considered universally applicable across all types of building structures and climates. However, these standards may fail to perform under many climatic conditions or in many different building types (Brager & deDear, 1998). Consequently, Brager and deDear also suggested a more-flexible thermal-comfort model in which users have more control over their environment.

Brager and deDear's (1998, p. 85) conceptual model of thermal adaptation considered the following behavioral and mechanical factors of adjustment:

1. Personal adjustments: changing clothing layers, postures, locations within a building; reducing or increasing activity; eating hot or cold liquids
2. Technological or environmental adjustments: modifying surroundings when control is available (e.g., opening windows or shades, turning on fans or heating, blocking air diffusers, operating HVAC controls)

3. Cultural adjustments: scheduling activities, sleeping preferences, adapting dress codes.

Brager and de Dear mentioned that behavioral adjustments of the body’s heat-balance levels allow users to be proactive and to determine their own thermal comfort (Brager & deDear, 1998). They argued that:

> Behavioral adaptation operates across several time scales. Cutaneous thermoreceptors provide almost instantaneous neural information about sudden changes in the thermal environment, as experienced, for example, when crossing the indoor/outdoor threshold, thus enabling clothing adjustments and other behavioral adaptations to be affected well in advance of any significant alteration in the body’s heat balance. (Brager & deDear, 1998, p. 86)

All the factors mentioned above will enable fast, efficient adaptation to thermal environments. Other researchers view thermal comfort as more complex and urge that other variables be considered. According to Dusan Fiala, et al.:

> Complete heat budget models take all mechanisms of heat exchange into account, and can be considered state-of-the-art. Input variables include air temperature, water vapor pressure, wind velocity, mean radiant temperature including solar radiation, in addition to metabolic rate and clothing insulation. Such models possess the essential attributes to be utilized operationally in most biometeorological applications in all climates, regions, seasons, and scales. (Fiala, Jendritzky, Staiger, & Wetterdinets, 2002)

Discussion and Conclusions

The adaptive thermal-comfort approach to determining thermal comfort was an important advance. Accounting for outdoor climatic conditions and what effects these may have on people’s thermal preferences as they transition into indoor spaces should be considered each time we design and define indoor thermal parameters for new or existing buildings. Individuals will feel more in control and more comfortable. In other words, people will react to their indoor environment using all the tools available to them (Brager & deDear, 1998). Adaptation strategies range from simply putting on a sweater to closing windows or turning on a fan. ASHRAE-55 2010 adopts a semi-adaptive thermal-comfort approach: it offers different thresholds for indoor thermal comfort for the summer and winter: 73–81°F for summer conditions and 68–76°F for winter (ASHRAE Standard 55, 2010). The adaptive thermal-comfort model also considers health factors, cultural preferences, access to HVAC controls, and access to building envelope attributes such as windows, doors, fans, or vents.

The adaptive model is reasonable and appropriate for most populations.
The literature indicates that, in some cases, many benefits will ensue: greater acceptance of indoor thermal conditions; greater tolerance to indoor temperature changes (as they may be the result of users making those changes); greater energy savings; and a greater perception of acceptability, even when temperatures fall outside of their comfort zone.

The "adaptive approach" may offer more benefits, yet it is uncertain how this mode will perform in locations with extreme climates, such Phoenix, Arizona.
For example, the almost-perfect adaptive thermal-comfort equation as characterized and proposed by Nicol and Humphreys would not offer comfort to most users living in a such an arid climate, where outdoor temperatures routinely reach triple digits (Nicol & Humphreys, 2002, p. 569). If we use 116°F as a maximum temperature for any given day in Phoenix, the adaptive thermal-comfort equation would function as follows:

$$T_C = (56.30) + (0.37 * T_O)$$

$$T_C = (56.30) + (0.37 * 116)$$

$$T_C = 99.22\ °F$$

The recommended indoor acceptable temperature for a climate like Phoenix during the summer would be 99.22°F. This temperature is considered not only uncomfortable but unhealthy for any population, especially for older adults and children. The Adaptive Thermal Comfort Model does not seem to be functional or recommended for extreme climates, although it may be implemented during seasonal transitions when weather is neither extremely hot nor cold.

The second deficiency is the lack of information on how this model may affect older adults' comfort and behavior. Older adults are rarely mentioned throughout the literature, sewing doubts that this approach might provide adequate comfort to that population. For example, it does not consider the physical limitations that older adults may have, such as a lack of strength or flexibility or weakness in reaching a fan chain or opening a window to alter their environment. Overall, it would be difficult to assess the efficiency of this model amongst older adults at different ages.

Finally, all the above authors focused on working environments and the working-age user, and assumed that everyone, even within those groups, can exercise control over that environment if given the opportunity. This assumption presents an even more serious issue in central-conditioned spaces, where older adults cannot exercise control of the indoor environment. Extreme outdoor conditions can compromise older adults' health and, in some cases, their lives. There is no mention of research in residential settings and the use the adaptive model in those environments.

As such, the thermal-comfort model does not meet the requirements for creating healthy indoor thermal environments. As proposed earlier, a hybrid thermal-comfort system would be the best fit for all populations conceptually. ASHRAE needs to revise its recommendations and parameters and, for both models, researchers need to study thermal variability and its impact on the comfort, health, and perceptions of older adults. We must validate each model and its efficacy in providing healthy and comfortable indoor environments for older populations.

Older Adults, Health, and Thermal Conditions

There is no debate that indoor environmental conditions affect the health, comfort, and ability of older individuals to lead a healthier life. "Older people are more prone to thermal-related comfort and health issues, including hypo- and hyperthermia. Thermal comfort, or the lack of it, is well understood to be one of the most significant restrictors to the health and general wellbeing of the older people" (Novieto & Zhang, 2010, p. 1). Indoor environmental quality is relatively simple to measure. However, the effects of these conditions on health are often difficult to assess. For example, finding the link between cancer and formaldehyde leaching from kitchen and bathroom cabinetry is difficult to evaluate; its effects may take decades to appear. Often, it is even more difficult to find a direct link between cancer, skin conditions, or respiratory issues to levels of aldehydes and other VOCs associated with indoor air quality. (Salthammer, Mentese, & Marutzky, 2010)

Temperature changes, however. have an immediate effect on activity levels, thermal sensations, perceptions, and overall comfort. Ultimately, indoor thermal attributes impact health and our ability to perform psychological and physiological activities (McGeehin & Mirabelli, 2001). In particular, high and low temperatures, as well as the constant changes of these indoor environmental conditions, affect older populations disproportionately (Novieto & Zhang, 2010). The ability to thermoregulate their core-body temperature in short periods of time diminishes with age. Decreased physical activity during the aging process partially explains this degradation (Havenith, 2001). Furthermore, Havenith explains, statistical evidence in the US and Japan reveals that older adult mortality increases dramatically with age and high temperatures, which might be the result of both, indoor thermal conditions and the inability of older adults to thermoregulate adequately and on time. On the other hand, in cold environments, older adults have more difficulties reducing heat losses/staying warm and fall more frequently, thus increasing the rate of injuries and broken bones and providing another reason to develop specific recommendations for older adult environments. Thermal comfort is not only about comfort but safety. Moreover, there is a delayed thermal sensation to cold temperatures that relates to their inability to thermoregulate as efficiently as younger adults (Tochihara, Tadakatsu, Nagai, Tokuda, & Kawashima, 1993). This problem is serious and may cause not only discomfort but possibly injury and death.

Existing research has shown that older adult's core-body temperature decreases with age. Temperature changes, especially temperature swings and fluctuations in short periods of time affect older adults disproportionately (Novieto & Zhang, 2010; Gomolin, Aung, Wolf-Klein, & Auerbach, 2005; Havenith, 2001). For example:

> Nursing literature often mentions the various indoor environmental parameters in relation to people with dementia in certain care settings, and provides clear indications in the form of anecdotal evidence that people with dementia are generally very sensitive to (changes in) indoor environmental parameters. Unfortunately nursing sciences have not yet yielded practical guidelines for the building sector how to create optimal indoor environments. (Van Hoof et al, p. 2)

Although dementia does not occur in many older adults, older adults can still be more sensitive to thermal changes within different periods of time. Their thermoregulatory capacities diminish with age, and they have more difficulty adapting to indoor environmental changes.

> With advancing age our ability to thermoregulate tends to decrease. This is a multi-factorial process involving many of our physiological systems with an emphasis on the cardiovascular system. The most important factor is that physical fitness tends to decrease with age, mostly due to a reduced physical activity level in the elderly. This implies that any activity performed becomes more stressful with advancing age. It will put more strain on the cardiovascular system, and leave less cardiovascular reserve. The cardiovascular reserve is especially relevant to the capacity for thermoregulation as it determines the capacity to move heat for dissipation from the body core to the skin by the skin blood flow. (Havenith, 2001, p. 41)

These differences are even more evident between genders. Men, for example, are more susceptible to cold temperatures, and mortality rates during cold weather are greater among older males in relation to comparably aged females (Schneider & Macey, 2003).

In relation to daily activities, older adults distribute their time differently from younger working-age individuals and use their residential space in different ways; for example, they may spend more time in their residences and spend little time in other spaces such as offices or commercial spaces. *TransWorld News* estimates that the average person spends 85 to 90% of their time indoors (TransWorldNews, 2010). Although this number needs to be more specific in terms of who and what groups spend that time indoors, it is true that younger adults who may be employed are more mobile and spend more money in entertaining and other activities, causing them to spend their time in more places. Lower-income older adults do not have this ability and spend most of their time within their living spaces (Donald, 2009). This excess of time spent indoors in one primary space can seriously impact older adults' physical and physiological health and comfort if their actual and perceived needs are unmet.

Age is one factor affecting the activity levels of adults and their ability to regulate core-body temperature. Other factors include illnesses and disabilities, such as dementia.

> The percentage of people with illnesses and disabilities increases with age as well. In the UK 41% of people aged 65-74 and 52% over 75 reported that their lifestyle was limited by an illness or disability, compared to 22% of all age groups. This also has consequences for well-being in various thermal environments. Drug use associated with illness often has a negative effect on thermoregulation too. (Havenith, 2001, p. 41)

Drug use and specific disabilities are not the concern of my research, however, it these conditions provide more justification for developing specific recommendations for indoor temperatures for older adults.

Links between thermal conditions, perceptions, comfort, and especially health have been examined in a wide variety of studies, yet these findings are fragmented and disconnected. Turnquist and Volmer in 1986 found an optimal indoor temperature for older adults of 77.54°F (Turnquist & Volmer, 1986); this temperature is much higher than the optimal temperature of 76°F that ASHRAE-55 2010 recommends for the summer.

This study was one of the first that determined the preferences of indoor temperatures of older adults, in a housing project which was similar to the one used for this dissertation. Turnquist and Volmer interviewed 34 of 88 residents, asking them to rate their thermal satisfaction. While the sample size is relatively small, it was conducted within a group of adults 62 years of age and older in a public multi-unit housing project, which makes this research even more relevant to this dissertation.

Other researchers (e.g. Havenith, Van Hoof, Thichara et al., and Rohles) conducting medical or physiological studies in built environments have found that older adults generally have mean oral body temperatures lower than the traditional 98.6°F (Gomolin, Aung, Wolf-Klein, & Auerbach, 2005). Gomolin, et al, acknowledge that this temperature standard should be discontinued, as it does not represent the conditions of all populations. Because older adults' core-body temperatures tend to be lower, a need is created for warmer living spaces for older adults in general. Rohles (1969) went beyond general assertions, stating that, "older persons over the age of 40 prefer temperature for comfort of 1°F higher than that desired by persons below this age" (Rohles, 1969, p. 37).

Developers of standards have not addressed many of these needs or studied them in depth. ASHRAE acknowledges the limitations of their Standard 55 and their PMV-PPD model; they explicitly affirm that these standards do not apply to sleeping or resting conditions, something that elders commonly do at various times during the day and/or for extended time periods.

> As adults age, difficulties in initiation and maintenance of sleep become a frequent health complaint. The difficulties are reflected in subjective complaints about the length of time needed to fall asleep, the number of nighttime awakenings, the duration of awakenings, and the amount of nighttime sleep obtained. (Floyd, Medler, & Janisse, 2000, p. 106)

Alapin, et al. further supported this argument: “The experience of Difficulty in Initiating and Maintaining Sleep (DIMS) is a common health problem that increases over the life cycle, its prevalence ranges from 30% to 40% in the general population and rises to 50± 60% in individuals over 60” (Alapin et all, 2000, p. 381). This argument is crucial to my research objectives. If the simple process of aging affects sleep patterns, indoor environmental factors are even more relevant. Temperature, then, becomes an important element that could either exacerbate sleeping disorders, create conditions with poor temperature quality, or provide a comfortable and stable environment in which older adults can sleep better.

Technology is another issue that older adults must confront when trying to create comfortable thermal conditions in their homes. Something as simple as a thermostat can represent a challenge; digital thermostats, for example, can be complicated to operate, creating a struggle to regulate their indoor environmental controls. The ability to understand technology and control these systems can be limited.

These individuals tend to manipulate their thermostats more often than younger adults, increasing or decreasing indoor temperatures frequently and exacerbating the level and frequency of fluctuations in their residences, which can create unhealthy or uncomfortable indoor thermal conditions (Van Hoof et all, 2008). A valid solution may be to install highly complex indoor environmental controllers.

A disadvantage to this solution, however, is that these systems can reduce the ability of individuals to interact with the outdoors, If too comfortable indoors, they may be less inclined for natural stimulation outdoors, and acclimatization to hot and cold fronts can be essential to prevent temperature-related illnesses (Havenith, 2001).

Older adults as explained by Novieto and Zhang (2010) are much more prone to temperature-related illnesses and, in some cases, extreme temperatures can be deadly. Irregular and extreme temperatures have killed vulnerable individuals on many occasions. “In the United States, an average of 274 people are direct victims of heat-related mortality each year, with the highest death rates occurring in persons at least 65 years of age” (Basu & Samet, 2002, p. 1219). Mackenbach, Borst, and Schols (1997) also supported this argument with another study concluded in 1997 in the Netherlands, in which they explained “that heat is definitely a high risk factor for older adult mortality.” These studies indicate that thermal conditions can not only decrease the ability of vulnerable populations to perform their daily activities or maintain their comfort but can be fatal (Yip, et al., 2008).

Other studies argue that higher temperatures are not often fatal, but instead present low-quality indoor thermal conditions that are uncomfortable and ill conducive to high productivity and a comfortable and healthy living. Fang, Fanger, and Clausen (1998) reported that individuals perceived air as less acceptable with increased temperatures and humidity. Older adults prefer slightly higher temperatures, but not too high, as they become counterproductive. Novieto and Zhang and other researchers support this finding, as older adults have lower core-body temperatures and therefore need more insulation and/or warmer and more-stable indoor environments. “In principle older adults do not perceive thermal comfort different from younger adults” (Van Hoof & Hensen, 2006). However, lower metabolic rates and lower levels of activity are some of the main reasons older adults need higher temperatures. General indoor air quality and thermal quality will affect the health and well-being of older users.

There is no doubt that thermal conditions not only affect older adults’ comfort, but their perceived and actual health and well-being. This dilemma will be magnified in the next 20 years with the impending retirement of those in the baby-boomer generation who will reach the age of 65 (USCensus Bureau, 2009). In 2008, 54.6% of older adults not living at a facility were living with their spouses or partners, which accounted for 11.3 million people, while about 30.5% or 11.2 million were living alone in 2008. As these individuals age, the percentage of older people living alone increases dramatically, especially for women, who after 75 years of age, account for 50% of all older adults living alone (Administration on Aging, 2009). Older adults living alone tend to adopt different attitudes to health and safety; Basu and Samet (2002() identified specific behaviors that result, including closing their windows and doors constantly or, in some cases, lacking air conditioning and keeping safe by closing their doors, which can increase indoor temperatures to high-risk levels (Basu & Samet, 2002).

Between these two groups, we have over 20 million older adults living alone or with their older spouses or partners; this population will be growing exponentially. Currently the US population is at 307 million, of which almost 40 million are 65 years or older. This population is expected to increase to 55 million by 2020, expanding the need for quality, healthy, and comfortable housing (United States Census Bureau, 2009); (Administration on Aging, 2009). Failing to provide these people with this basic commodity called "healthy housing" could impair public health and severely stress our health and economic sectors. See Table 4 for expected population growth.

Table 4
Older Population in the US

Total US Population 2010	Current US population 65+	Older adults 65+ living with partner in 2008	Older adults 65+ living alone in 2008	Expected US population 65+ by 2020
307,006,556	40,000,000	11,300,000	11,200,000	55,000,000

Discussion and Conclusions

The literature clearly indicates that older adults have different needs and preferences for thermal conditions. However, few studies evaluate the impact of temperature fluctuations on perceived or actual health and comfort in older adults. We can safely assume that older adults prefer warmer temperatures due to lower core-body temperatures and, on average prefer ~2°F higher temperatures at indoor environments. Researchers have established that this preference results from lower metabolic rates and activity levels as people age. (Gomolin, Aung, Wolf-Klein, & Auerbach, 2005). Both Gomolin and Havenith agreed that whether due to low metabolic rates or less physical activity, older adults prefer slightly warmers environments.

Environmental psychologists, medical specialists, engineers, and designers have centered their research in residential settings (Heijs & Stringer, 1988; Fox et al., 1973). In contrast, research organizations like ASHRAE and ISO have conducted most of their research in working places, particularly office areas. The combination of the research on older adults' thermal comfort and the standardization industry could enhance conceptual and applied research on thermal comfort for older adults at different ages.

The fragmented nature of the research defines this field; researchers use different methods, population groups, and climatic conditions. These studies included one with only 40 subjects and another with 100 subjects (Salvosa, Payne, & Wheeler, 1971).

More collaboration on a global scale and across borders could enhance current knowledge. In addition, already-collaborating organizations like ASHRAE or ISO are poised to craft recommendations for standardizing thermal conditions for older adults.

Primary Concepts

A review of the literature reveals two primary concepts, that will leads us to better address the thermal-comfort needs for older adults in residential environments.

1. Core-body temperatures decrease with age, due to declines in metabolic rates; thus, older adults require higher indoor temperatures (Havenith, 2001; Kenney & Munce, 2003; Gomolin, Aung, Wolf-Klein, & Auerbach, 2005).
2. Thermoregulation ability diminishes with age. Thus, unstable and frequent indoor temperature changes or temperature swings affect older adults more.

These concepts suggest the need for more-specific recommendations for thermal conditions for older adults, especially for those with disabilities such as dementia (Kenney & Munce, 2003; Novieto & Zhang, 2010; Gomolin, Aung, Wolf-Klein, & Auerbach, 2005).

Chapter 3

METHODS

Chapter 3 describes the conceptual model, methods, sampling, procedures, and quality-control protocols of this research study. I outline research questions, subquestions, and corresponding hypotheses, along with data collection, data processing, data preparation and statistical analysis. The methodology is directed by three primary questions that were developed for this project: a) How does indoor temperature affect the health and comfort of adults 60 and older? b) How do temperature fluctuations affect their health and perceived comfort? c) Are the SENIOR COMFORT Metrics 2013 better indicators than the ASHRAE-55 2010 Standards for examining temperatures and their effects on the health and perceived indoor thermal comfort of older adults? These questions, sub-questions and corresponding hypothesis are further developed and explained in this chapter.

Conceptual Model

The conceptual model shown in Figure 2 details the sequential development of my study. The model was designed partly from the hypothetical premise that slightly warmer and steadier indoor thermal conditions will benefit the actual health and perceived comfort of older adults. I used two metrics to test this hypothesis; one includes the well-established ASHRAE-55 2010 parameters for indoor thermal conditions.

The alternative proposed in this study is the new SENIOR COMFORT Metrics 2013 (described in more detail in a following section). Researchers including Gail Brager, Richard de Dear, Fergus Nicol, and Michael Humphreys have developed preliminary alternative recommendations for different metrics or thresholds, but again, none of them focus on older adults or residential environments. As a result of their medical and physiological studies, Turnquist, Havenith, Larry, Munce and Gomolin, among others, have proposed that older adults prefer higher temperatures between 1 and 3°F. However, none of these medical researchers have proposed a clear metric or new thermal-comfort threshold that best fits most-older adults, thus opening the door for the alternative threshold proposed here.

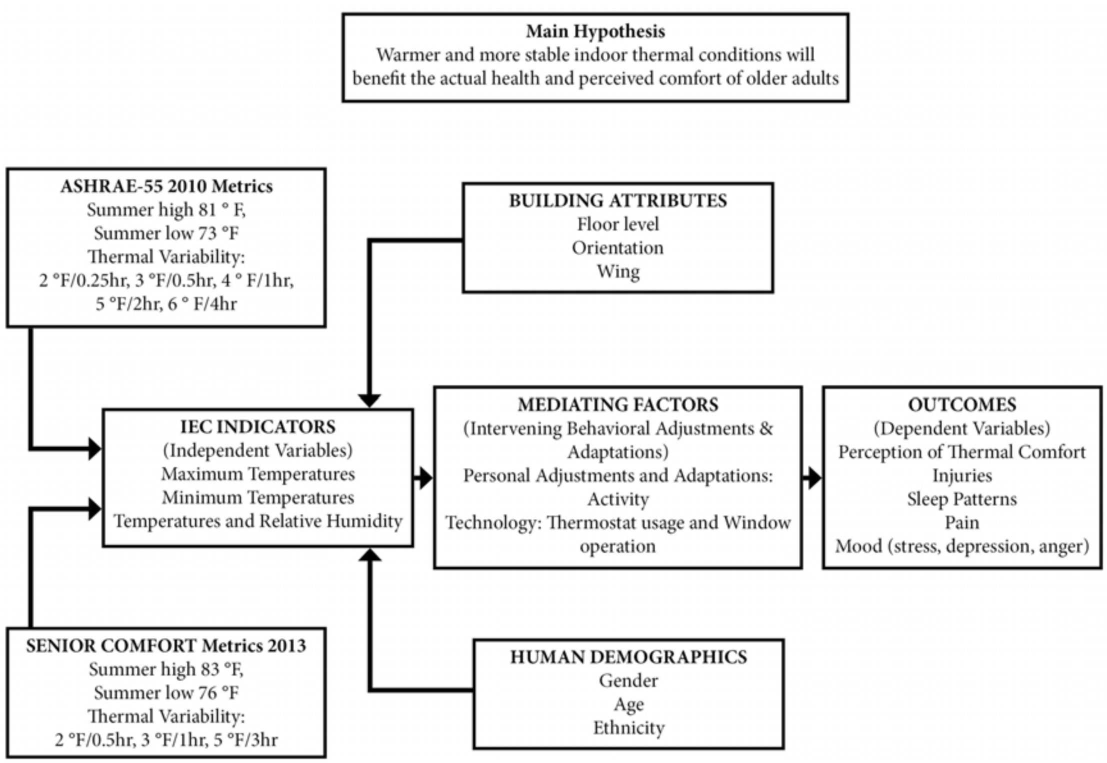

Figure 2. Conceptual Model ASHRAE Standard-55 2010 and the proposed alternative, the SENIOR COMFORT Metrics 2013

Both systems; the ASHRAE-55 2010 and the SENIOR COMFORT Metrics 2013 outlined recommendations regarding minimum and maximum temperatures and temperature fluctuation ranges within specific periods of time.

The conceptual model is structured in three sections and two subsections. This structure allows for the model to organize information and direct research flow in a systematic approach. The model was designed partly from my main hypothesis that states that warmer and more-stable temperature conditions will benefit the actual health, perceptions, and thermal comfort of older adults.

The SENIOR COMFORT Metrics 2013

I developed the SENIOR COMFORT Metrics 2013 based upon aggregate information found in the literature review. Gomolin et al., Novieto and Chang, and others, determined that the accepted and generalized core-body temperature of 98.6°F is not necessarily adequate when measuring the temperature of adults 40 and older. Other authors, such as Turnquist and Volmer, suggested a 77.54°F optimal ambient temperature for older adults, 1.54°F higher than that calculated by ASHRAE-55 for summer conditions. The maximum temperature for summer recommended by ASHRAE-55 2010 is 81°F. Based upon this baseline, the SENIOR COMFORT Metrics 2013 recommend a 2°F increase or 83°F maximum and a 76°F minimum. ASHRAE-55 2010 recommends 73°F.

Variability, as outlined in ASHRAE-55 2010, recommends five thresholds that allow for greater variability in relation to the SENIOR COMFORT Metrics 2013. The new metrics allow only three thresholds with tighter intervals of time and degree changes overtime for variability.

This study recognizes the extraordinary work of Pov Olev Fanger, Brager, De Deer, Humphreys, other researchers, as well as ASHRAE and ISO, and the importance of their thermal-comfort model and structure. The SENIOR COMFORT Metrics 2013 adopted a similar structure for outlining thresholds and parameter to be tested, such as temperature limits and variability.

Variables and Metrics

This section describes and defines the different components of the conceptual model and data associated with those components for indoor thermal conditions and self-reported health interviews.

Temperature Predictors

Temperature predictors refer to an apartment unit's specific indoor absolute air temperature and relative humidity. These predictors are the independent variables and include maximum and minimum temperatures, maximum and minimum relative-humidity levels, and thermal variability over specified periods of time. Existing ASHRAE-55 2010 standards have outlined specific thresholds; the alternative proposal, the SENIOR COMFORT Metrics, outline other thresholds that may better predict older adults' overall thermal comfort. Relative humidity was measured to ensure that fall within recommended thresholds as outlined by ASHRAE. No further analysis was conducted with relative humidity.

Maximum and Minimum Thermal Thresholds

I analyzed two attributes of indoor temperature and humidity quality: temperature extremes and their variability over specific periods of time. The same attributes apply for indoor relative humidity. This section defines the various thresholds for high and low temperatures, relative humidity, and thermal variability. These thresholds are based on the Standard ASHRAE-55 2010 Metrics and the newly proposed SENIOR COMFORT Metrics 2013:

1. Maximum and minimum temperatures and indoor relative humidity refer to highest and lowest temperatures and humidity levels recorded at a given time.
2. Temperature variability or cycling temperature variations refer to temperature changes over a specific period of time. ASHRAE-55 2010 defines this concept as situations where temperature repeatedly rises and falls and the period of the fluctuation is not greater than 15 minutes (Table 5).

Table 5
ASHRAE-55 2010 Max and Min Thresholds

Temperatures		Temperature Variability Over Time					
Maximum	81^{o}F	Fluctuation in ^{o}F	2	3	4	5	6
Minimum	73^{o}F	Time Period in Hours	0.25	0.5	1	2	4

The SENIOR COMFORT Metrics define temperature variability as changes within a specific period of time and in intervals no greater than 30 minutes (Table 6).

Table 6
SENIOR COMFORT Metrics Min and Max Thresholds

Temperatures		Temperature Variability Over Time			
Maximum	83 ^{O}F	Fluctuation in ^{O}F	2	3	5
Minimum	76 ^{O}F	Time Period in hours	0.5	1	3

Note: Relative humidity was not considered for this study.

Temperature Factors

Two sets of factors—moderating and mediating—affect temperature. Moderating factors account for to building attributes and population demographics. Mediating factors represent a direct response to indoor ambient temperatures and include changes in activity levels, clothing, HVAC manipulation, and window or door adjustments.

Physical Building Attributes' Moderating Factors

Two physical building attributes were recorded: the floor level of apartment units, (recorded as lower floor, second floor, or third floor) and the orientation of the apartment unit (recorded as north, south, east, or west).

Human Demographics and Health-Moderating Factors

Resident's demographic information includes only age, gender, and ethnicity and was collected in person, through a self-reporting health survey administered by Arizona State University's (ASU's) Institute for Social Science Research (ISSR).

Composite Development

Ten data composites were developed within three groups; each composite was identified as the research was conceptualized and mapped. Based on recommendations found in the literature and model development, I outlined IEC predictors (independent variables and outcomes), moderating factors, and outcomes.

1. IEC predictors composites
    a) Maximum temperature composite
    b) Minimum temperature composite
    c) Temperature composite
2. Mediating factors composites
    a) Activity for Personal Adjustments and Adaptations
    b) Thermostat Usage and Window Operation for Technology
3. Outcomes composites
    a) Perceptions of thermal comfort
    b) Injuries
    c) Sleep patterns
    d) Pain
    e) Mood (stress, depression, anger)

IEC Predictors Composites

1. Maximum Temperature: I collected temperatures in three different locations within the livable space. All maximum temperatures among those three spaces were not significantly different. Chronbach's alpha reliability

estimates yielded results over α=0.9 when testing the similarity of temperature thresholds.

I combined all maximum temperatures into one composite and used the mean of those three spaces to develop the maximum temperature composite.

2. Minimum Temperature: I collected temperatures in three different locations in the livable space. Chronbach's alpha reliability estimates yielded results over α=0.9 when testing the similarity of all temperature thresholds. All minimum temperatures among those three spaces were not significantly different.

   I combined all minimum temperatures into one composite and used the mean of those three spaces to develop the minimum temperature composite.

3. Temperature (mean temperature): I collected temperatures in three different locations within the livable space. Chronbach's alpha reliability estimates yielded results over α=0.9 when testing the similarity of all temperature thresholds. All mean temperatures among those three spaces were not significantly different. I combined all the mean temperatures into one composite and used the mean of the three means of those three spaces to develop the temperature composite.

Mediating Factors Composites

Mediating factors refer to those factors that will not affect the independent variables, but instead are a direct human response—behavioral adjustments and adaptations—to those predictors. These factors were measured through questions from four national surveys, the National Health Interview Survey (NHIS) administered by

Center for Disease Control and Prevention (CDC, 2013), the Behavioral Risk Factor Surveillance Survey (BRFSS) administered by the CDC in 2013 , the Real Estate Assessment Center Survey, administered by the US Department of Housing and Urban Development, (HUD, 2013) and the Occupant Indoor Environmental Quality Survey (IEQ Survey) administered by the Center for the Built Environment at the University of California Berkeley (CBE, 2013)

For this study, 40 questions and 20 sub-questions were selected to assess indoor thermal conditions and their effects on the perceived comfort and the actual health of older adults. These questions were organized based on subsections outlined in the conceptual model. Each one of those subsections was supported through survey questions. Simultaneously, those questions were organized in groups or composites in order to strengthen validity and results.

The detail development of these composites will be further explained in this chapter.

The following questions were selected for the moderating factors' sections and subsections.

Table 7
Personal Adjustment and Adaptation Composites

		Activity
1	General Questions	How difficult is it for you to walk up 10 steps without resting?
2		How difficult is it for you to stand or be on your feet for about 2 hours?
3		How difficult is it for you to sit for about 2 hours?
4		How difficult is it for you to stoop, bend, or kneel?
5		How difficult is it for you to reach up over your head?
6		How difficult is it for you to use your fingers to grasp or handle small objects?
7		How difficult is it for you to lift or carry something as heavy as 10 pounds, such as a full bag of groceries?
8		How difficult is it for you to push or pull large objects like a living room chair?
9		How difficult is it for you to participate in social activities, such as visiting friends, attending clubs and meetings, and going to parties?
10		How difficult is it for you to do things to relax at home or for leisure?
		Use and Manipulation of Technology
1	General Qs	Is it difficult to control your heating?
2		Do you use air conditioning for comfort?
3		Do you use air conditioning and open the windows at the same time?
4	Do you personally adjust or control in your unit	Window blinds or shades
5		Operable window
6		Thermostat
7		Portable heater
8		Permanent heater
9		Room air-conditioning unit
10		Portable fan
11		Ceiling fan
12		Adjustable air vent in wall or ceiling
13		Adjustable floor air vent (diffuser)
14		Door to exterior space
14	Window Manipulation	Do you open the windows for comfort?
15		Do you use air conditioning and open the windows at the same time?
16		Which of the following do you personally adjust or control in your unit?
17		Window blinds or shades
18		Operable window

Outcomes Composites

These factors are the resulting health conditions of all predictors and their interactions. These measures include: perceptions of thermal comfort, physical injuries, sleeping patterns, pain, and mood. I developed five outcome composites based upon the 40 questions and 20 sub-questions extracted from national surveys. Questions were organized rationally, based upon their relation to each other and on one of the five measures mentioned above: perceptions of thermal comfort, physical injuries, sleep patterns, injuries and mood. Questions assessing similar content were grouped in five different composites reflecting the outcomes mentioned below.

Table 8
Outcome Variables Composites

		Perceptions of Thermal Comfort
1	General Questions	How would you rate the comfort of your home in terms of temperature in the summer?
2		How satisfied are you with the temperature in your unit?
3		Overall, does your thermal comfort in your unit enhance or interfere with your comfort?
4		How satisfied are you with the following aspects of your kitchen? Q108b
5		Please indicate how satisfied you are with the effectiveness of your thermostat? Q109a
		Physical Injuries
1	Issues that make you rely on others for help	Vision/problem seeing
2		Back or neck problem
3		Fracture, bone/joint injury
4		Other injury
5		Lung/breathing problem(e.g., asthma and emphysema)
6		Cancer
7		Depression/anxiety/emotional problem
8		Weight problem
9	General Qs	Have you ever seen a doctor or other health professional for a skin condition?
10		During the past three months, did you have neck pain?

11		During the past three months, did you have lower back pain?
12		During the PAST 12 MONTHS, that is, since (12-month ref. date), ABOUT how many days did illness or injury keep you in bed more than half of the day (including days while being an overnight patient in a hospital)?
13		In the past 3 months, how many times have you fallen?
		Sleep Patterns
1	General Questions	During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?
2		During the past 30 days, have you had trouble with any sleep issues like falling asleep, staying asleep or sleeping too much?
3		Do you snore?
4		During the past 30 days, for about how many days did you find yourself unintentionally falling asleep during the day?
		Joint
1	General Questions	During the past three months, did you have neck pain?
2		During the past three months, did you have lower back pain?
3		Did this pain spread down either leg to areas below the knees?
4		During the past 3 months, did you have severe headache or migraine?
		Mood
1	General Questions	During the past 30 days, how often did you feel so sad that nothing could cheer you up?
2		During the past 30 days, how often did you feel nervous?
3		During the past 30 days, how often did you feel restless or fidgety?
4		During the past 30 days, how often did you feel hopeless?
5		During the past 30 days, how often did you feel that everything was an effort? Q53
6		During the past 30 days, how often did you feel worthless?

Data Collection, Process, and Quality Control

I and other team members surveyed a total of 73 apartment units and collected data in those units. Seventy-seven participants were initially interviewed in person and responded to a health survey;

I designed, developed, and implemented multiple measures and data collection strategies to accomplish data-collection goals. One participant declined to continue with the project; consequently, no thermal data was collected on that person's unit, and hence the sample size for this study is 72 units. In this section, I evaluate only the thermal data and surveys. Building and demographic attributes were recognized in previous sections, as were questions for mediation factors and outcomes.

Temperature and Relative Humidity Data Collection

Temperature and relative-humidity loggers were installed according to the plan in Figure 3. The legend on the plan responds to the type of logger installed in each location. TEMP01 can record only temperature; TEMP02 is the same as TEMP01; and RH03 is can log both relative humidity and absolute air temperature (See Appendix B for a full floor plan of the apartment units and logger locations).

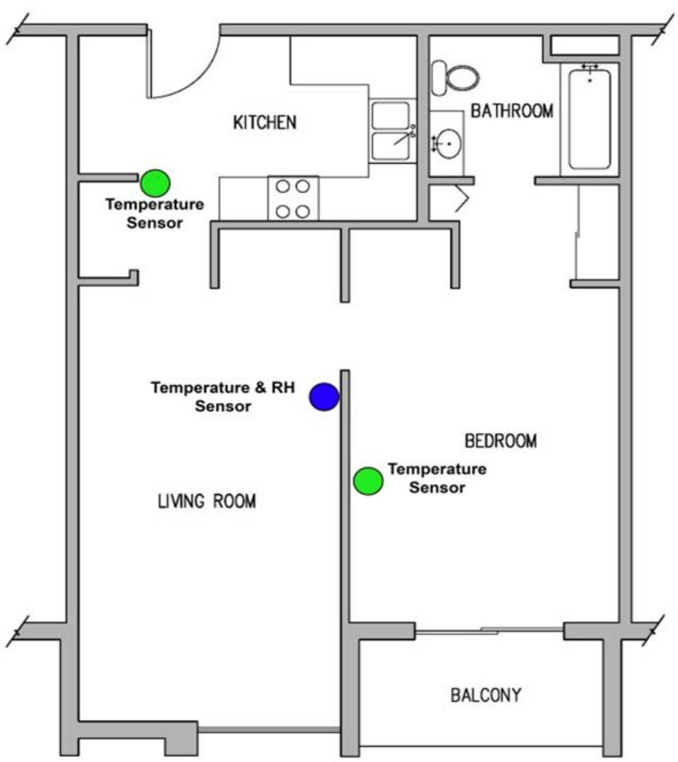

Figure 3. Thermo-sensor floor plan

Absolute air temperatures were monitored and recorded every 15 minutes in the kitchen, the bedroom, and the living area, using mobile ONSET-HOBO data loggers. For kitchens and bedrooms, a HOBO
U-10-001 was used, and for the living area, a HOBO U-10-003 was used. The latter data logger can measure both absolute air temperature and relative humidity; the HOBO U-10-001, however, can measure only absolute air temperatures. Each HOBO was installed at ~4-feet high, or midway between the floor and the ceiling, against the wall in the tested rooms. All HOBOs remained in place for five full days, recording 448 usable data points; any additional points were disregarded.

Relative humidity was monitored and recorded every 15 minutes in the living area only, using an ONSET-HOBO data logger U-10-003. This HOBO can record both absolute air temperature and relative humidity. Like the HOBO U-10-001, each HOBO was installed at ~4-feet high or midway between the floor and the ceiling against the wall in the living area for five full days, recording 448 data points; any additional readings were disregarded.

Since relative humidity in the units never registered values either above or below the recommended comfort zone, its effects on comfort are difficult to assess. There were no questions asked in this regard and, considering that relative humidity levels were within recommended thresholds by ASHRAE-55, relative humidity was not deemed to be a determining factor affecting health and/or comfort for this study. This particular parameter was not further assessed after the data-gathering stage for this study.

Health Survey Sources and Procedures

A second set of variables corresponds to a self-reporting health survey that ISSR administered, supervised by the Green Apple Team (GAP) at ASU's Stardust Center for Affordable Homes and the Family. Selected survey questions were extracted from pre-existing national health questionnaire, including the National Health Interview Survey (NHIS), which is annually administered by staff members from the US Census Bureau (USCB). The NHIS uses 600 interviewers, directed by health survey supervisors in 12 USB regional offices across the US. The second national survey used for health questions was the Behavioral Risk Factor Surveillance System Survey (BRFSS), which was administered via phone call by trained interviewers. These two instruments were selected as the preferred sources for health questions because they are highly recognized national health surveys used by health professionals, researchers, and US Department of Health and Human Services National Centers for Disease Control and Prevention.

The NHIS and BRFSS surveys measure and examine sensory impairment, functional limitations, mental health, sleep patterns, assistance with diabetes, joint ailments, pain, hearing problems, skin conditions, emotional support, life satisfaction, and health-related quality of life (Ahrentzen & Fonseca, 2010). According to co-investigator and dissertation committee member Kimberly D. Shea, PhD and RN, selected health questions were based on two criteria: that these questions relate to quality of life, mood, general health, and/or happiness; and, that these questions inform the researcher on functional aspects of the interviewees, which could limit mobility and independence and cause injuries, pain, diabetes, or respiratory ailments. These questions were selected specifically for adults, 60 years of age or older, and considered their possible health and behavioral conditions. This information was obtained during a formal interview with Dr. Shea at the University of Arizona in 2012. (Shea, 2012)

A third survey was used to provide questions about indoor environmental quality and its effects on residents and other users. In this case, the GAP team selected the Occupant Indoor Environmental Quality (IEQ) Survey from the CBE; the CBE is embedded within UC Berkeley's College of Environmental Design, a leader in environmental design and testing. The selected questions related to the impact of temperature or humidity on the comfort of residential occupants (CBE, 2010).

Recruitment

To recruit as many participants as possible and to disseminate information, answer questions, and minimize concerns regarding the City of Phoenix's green remodel and my research project, I conducted an informational workshop with potential respondents. All residents at Sunnyslope were approached personally, via flyer, and/or via poster boards in their main common areas, inviting them to participate in the study. In addition, the Stardust Center, in collaboration with the City of Phoenix and Sunnyslope management, organized a recruitment event during which their representatives presented information on proposed renovations and my study. Stardust Center representatives were divided into two teams: health and IEQ. Both teams explained the tests and measures to take place, including indoor environmental testing and self-reported health interviews.

As an incentive to attend, registered nurses provided free blood- pressure tests; the Stardust Center raffled gift cards; and refreshments were served. The Stardust Center provided translations for all Romanian and Spanish speakers. Participants were offered $25 gift certificates after completion of their interview and gathering of data per Panel I. Three total panels were designed for the complete Green and Health Homes study; however, just one panel was used for the dissertation research.

After participants were signed up, they were scheduled for a home visit, for interviews and indoor environmental data collection. Before the interview and testing process, participants were asked to sign a consent form, translated into Spanish, Romanian, Farsi, or Russian languages. The form detailed the research project and participant rights, emphasizing that they could withdraw at any time without any penalties. Before the project began, in an effort to protect the rights of the participants, all investigators and co-investigators completed the CITI or NIH training course. This study originated from the greater Green Apple Project study sponsored by HUD. The entire study was designed in accordance to ASU’s Office of Research Integrity and Assurance (ORIA) policies and procedures, subject to the approval of the Institutional Review Board. The ORIA approved all protocols and procedures on May 5, 2010.

Sample Size

Several studies conducted in residential settings studied temperature and its effects on some aspects of health in older adults. These studies focused their research on very specific areas, for example, core body temperature, indoor temperature and injuries, urine temperature and age, thermoregulation and metabolic rate, etc. Their sample sizes varied, from 20 to almost 90 cases, Carmencita Salvosa, et al. analyzed 40 cases; (Salvosa, Payne, & Wheeler, 1971); Yutaka Tochihara and his partners studied 20 cases (Tochihara, Tadakatsu, Nagai, Tokuda, & Kawashima, 1993), with only one study consisting of a sample of more than 10 residents in relation to my study; the Hwang and Chen study which consisted of 87 subjects (Hwang & Chen, 2010).

Two factors determined the participant size at Sunnyslope: 1) the studies mentioned above, although researchers did not to take a holistic approach when analyzing thermal conditions and health or perceptions of thermal comfort, their sample sizes were a starting point; and 2) an initial power analysis was conducted with a medium effect size of r=0.30, alpha of .05 and a power of 0.80. It was determined that the sample size to detect a significant effect was 64. We engaged 76 participants.

Sample Description

The final participating resident count for this study was 76 residents and 72 units, 4 units of which were double-occupied. Most participants were female: 55 (71.4%) were female and 22 (28.6%) were male. I expected this gender distinction, as women typically live longer than men. The mean age was 74.21 years with a minimum age of 62 years and a maximum age of 92; the oldest resident in the apartment complex was 102 but did not participate. The age range was 30 years, with a standard deviation of 7.94.

Sixty-two (80.5%) participants reported to be of Caucasian descent, while 15 (19.5%) residents reported to be from another race, including Latinos, Hispanics, African Americans, Asians, Arabs, and others; 12 (15.6%) individuals reported to be Hispanic or Latino; this group represented the greater majority of the non-Caucasian minority.

Sixty-nine (89.6%) of the participants reported to be retired and not actively working; the disciplines of their former employment activities were diverse.
Sales, health-care support, and education categories dominated; 29 participants reported having worked in these sectors before retirement. Other employment industries included legal services, community services, framing, and construction.

Length of tenure at Sunnyslope was diverse. One (1.30%) resident reported living there for 30 years, while 9 (11.7%) reported to living there for 2 years, and 3 (3.9%) residents reported living there for 3 months. The mean tenure was 5.54 years, with a median of 3.75 years, a standard deviation of 3.75 years, and a full range of 29.95 years. Eight (10.4%) participants reported living outside Sunnyslope in the 6 months before the study.

Most participants lived alone, however 8 (10.4%) reported living with another person, and 24.7% had healthcare providers help them with daily chores. Of these, 19.5%

were assisted once a week. Six (7.8%) reporting being in poor health; 22 (28.6%) fair health; 35 (45.5%) good health, 11 (14.3%) very good health, and 3 (3.9%) excellent health.

Site Selection

In 2009, HUD awarded the City of Phoenix $1.7 million of stimulus funds to retrofit Sunnyslope Manor (Figure 4). The objective of the project was to perform a green retrofit in apartment units where the age bracket was concentrated in a single location. Sunnyslope, which the City administers, was an ideal site for a study on health and building indoor environmental conditions. After this award was announced, Stardust Center investigators, myself included, contacted the City's Housing Department to propose a study on health, green-building indoor environmental quality, and the associated economics surrounding these issues. The Department agreed to our proposal and collaborated with the ASU Stardust Center to move forward and support the Center's application with HUD.

Figure 4. Sunnyslope Manor Housing Complex

The Stardust Center was later awarded $450,000 to conduct a Green and Healthy Homes Technical Research Study at Sunnyslope.

Sunnyslope Manor Public Housing Complex

Sunnyslope is an assisted housing, midrise (3-story) development with 116 single- bedroom apartments for individuals or couples 62 or older. To qualify for this assisted housing, applicants must meet low-income thresholds. Development was completed in 1970 using block construction; the roof and subfloor structures were built with traditional wood frame trusses and rafters. Minimal insulation was identified in construction plans: 1.5 inches of BATT insulation on the inside of exterior wall provides the only insulation. Windows and sliding balcony doors were equipped with single ¼-inch clear glass, with uninsulated aluminum window frames. No unit had ceiling fans, but all were equipped with single Packaged Terminal Air Conditioning (PTAC) cooling and heating systems with a single-adapted-two-vent duct line to distribute air between living spaces and the bedroom; these systems are user-operated with a simple dialing thermostat. All units have a single-entry access through a shared central distributing corridor and balcony access through a patio door located in bedroom.

The building is oriented east-west, sitting on its long axis with 50% of apartments facing south and 50% facing north. All common areas, including offices and other social spaces, are serviced with a central cooling and heating. North-facing apartments are not exposed to direct solar radiation in the summer. The ground floor and the second floor are the most-insulated floors, considering that the third floor protects them from any direct solar radiation on the roof. The south façade has limited vegetation, with four medium-sized trees that shade some apartments. The northern lower apartments are slightly more insulated, with seven medium-sized trees; however these attributes were not considered for the analysis of indoor thermal conditions, as their vegetation canopies were minimal.

Typical Apartment Unit

All apartment units at have the same configuration (Figure 5); the main access to the unit is from the 122 SQF kitchen, followed by the living and dining rooms, which have a combined 233 SQF. Next to this living and dining space is the bedroom, with 197 SQF and a bathroom with 66 SQF. All units except two have an open balcony with a 6x6 foot sliding door; the only other light well is a 5x6 foot window in living room. The total livable indoor area is 620 SQF.

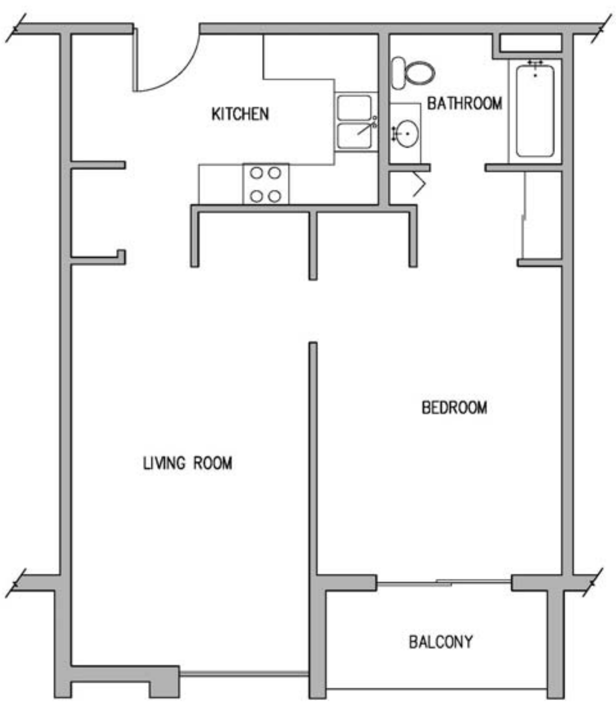

Figure 5. Typical apartment unit

The interior of each unit was constructed with traditional frames and drywall and finished with texturized paint. Interior walls are not insulated and allow for sound transmission from apartment to apartment. Exterior walls affect the living area and the bedroom; these walls are part of the overall building envelope, built with uninsulated concrete blocks. These walls are insulated internally with a 1.5 inch furring layer of BATT insulation. The actual thermal resistance value of that layer is unknown.

Each unit is equipped with a PTAC SEER 12 single outlet, which is internally split into two air outlets to provide air to the bedroom and the living areas. All units are painted white with a traditional tan mid-pile carpet. Roof ceilings are eight-feet tall, and main access doors are 36-inches wide, providing access to wheelchairs; only 11 units are ADA accessible. Apartments are equipped with traditional four-burner electric ranges, one 30-inch refrigerator, and two exhaust fans, one in the kitchen and one in the bathroom. None of the apartment units had a dishwasher, washer, or dryer. Laundry facilities are centralized along the main complex corridors on each floor.

Quality Control, Validity, and Reliability

To determine if collected data collected met the appropriate quality standards and objectives, data were submitted to a verification and control-process protocol. A minimal amount of faulty data that could not be re-collected or corrected was eliminated from the database and not considered for the final data analysis. Faulty data corresponded to small spots of temperature recording in which the data logger did not record data for periods of 15 minutes. When faulty data was found, the average between the previous and subsequent points was used as valid.

1. **Temperature and Humidity:**

   I used HOBO data loggers to collect data. I specified appropriate locations and heights, as well as minimal number of data points collected per week (see Appendix B for the HOBO data location plan).

After all loggers were removed from the participant apartment units, digital data were reviewed and approved; if data was faulty, incomplete, or damaged, new loggers were installed and data collection was repeated.

2. **Temperature and Relative Humidity:**

   Collection was accepted if it complied with protocols. I documented any serious deviations from protocols in all tested units (100%); 5% of these units were randomly selected tested twice, using two loggers per location to ensure instrument accuracy, errors, unusual deviations, and instrument reliability.

3. **Health Self-Reporting Interview Data:**

   Trained personnel from ASU's Institute for Social Science Research (ISSR) administered the interviews. ISSR personnel met in person with all participants independently and verbal asked all 110 questions. The questions were further explained if a resident did not understand the question as it written.

   The interviewer would then input all answers into a pre-programmed questionnaire in a laptop. The participant's unit number was recorded in the computerized system. If a resident did not speak English as a primary language, a translator was made available. When the survey was complete, the interviewed saved the file as a final submission in the computerized system and the interview was concluded. The interviewer would then thank the participant and exit the unit. To ensure compliance with protocol, Ahrentzen and Shea audited 5% of all units by visiting the interviewer while the survey was being conducted.

4. **Sunnyslope:**

   The 116-unit apartment complex was studied via architectural plans and many walk-throughs. I identified all units based on location and level. Data was collected on all floors, in all wings, and from all orientations.

Verification

I verified all data to ensure that the outlined criteria were met. The following items were taken into consideration when verifying all data:

1. **Conformity:**

   All thermal data sets were standardized at 448 data points recorded. This number was verified in all datasets. All data documented on paper was compared with actual data on digital files. This same procedure applied to the survey. If any data was missing by over 5%, data collection on that unit was repeated.

2. **Accuracy:**

   Periodic audits were conducted before data collection and during the interviews, to ensure compliance with and accuracy of procedures; 5% of all data collection for both interviews and IEQ sampling were formally audited for this purpose.

3. **Completeness:**

   All thermal data was collected and entered into Microsoft Excel worksheets, and imported into SPSS. Sets with <5% or 23 data points of scatter missing data points were allowed to stay. The previous and subsequent values were averaged to fill missing data points. This strategy does not jeopardize the reliability of the data. According to preliminary data analysis, this strategy had no impact on final results, means, highs, lows, or variability. Five percent of all units were dually tested.

4. **General:**

   All data was subjected to a rigorous preliminary analysis, which included visual assessment. Outliers were identified in SPSS electronic files to seek potential errors and solutions.

Data Analysis

Data was organized in relation to the three main predictors' sections:

- IEC predictors (Independent variables), including its moderating factors
- Mediating factors (Intervening Behavioral Adjustments and Adaptations)
- Outcomes

All predictors and their variables were subjected to the following data-analysis protocol:

- Data Preparation and Preliminary Analysis
- Identification of Predictor Composites
- Reliability Analysis (Cronbach's Alpha Test)
- Missing Values Identification and Removal

Data Preparation and Preliminary Analyses

I analyzed all data to determine reliability, completeness, and accuracy.

Before statistical analysis, I subjected all data was subjected to the following processes:

Reliability Analysis (Cronbach's Alpha Test):

I subjected correlations among different variables to a preliminary reliability analysis to identify and justify the formation of composite groups. I applied this reliability analysis to correlations among health-survey questions, temperatures between spaces, temperatures between floor levels and wings, and health questions with multiple subsections.

Frequencies and Descriptives:

I obtained frequencies and descriptive information for all interview questions to indicate their accuracy and usability. This step allowed me to identify and eliminate outliers and other faulty information.

Standardization:

During the formation of composites, some questions had different measuring scales. Questions with yes and no options that were asked as negation questions were standardized as direct questions. Questions with different Likert scales were standardized through SPSS z-scores.

Missing Data:

I identified missing data for all questions as Missing Values and eliminated during data preparation.

Identification of Composites

I subjected all composites to a Reliability Analysis to determine affinity among questions included in any given composite. Questions and composites with a correlation <0.7 were eliminated or treated independently as a separate variable. Composites that included yes and no answers will normally show a lower reliability factor, due to their nature and limited scale; consequently, these composites do not have to meet the 0.7 correlation threshold and instead a 0.3 r value was considered an acceptable threshold.

Research Questions

The following research questions address the issues and deficiencies identified in the literature review. These questions are derived from a main overriding question that explores how temperature and relative humidity affect the actual and perceived health and the thermal comfort of older adults. For this study, relative humidity did not represent an issue of concern for indoor thermal comfort; it fell within the prescribed comfort zone and recommended thresholds, and therefore I did not analyze this parameter further.

I developed several subquestions to answer specific concerns related to absolute temperature, human behavior or responses to indoor temperatures, perceptions, and actual health. Temperature variations are critical and will be examined as they affect the actual health, perceptions, and thermal comfort of older adults.

The SENIOR COMFORT Metrics 2013 represent a new system, proposed to measure the actual thermal comfort, actual health, and perceptions of thermal comfort of older adults. They aim to identify better indoor thermal condition recommendations for thermal variability and preferred absolute temperatures for that particular population.

Three primary questions and research hypotheses were developed related to temperature variability, temperature extremes; and the effectiveness of existing standards as predictors of thermal comfort.

Primary Questions

1. How does indoor temperature affect the health and comfort of adults 60 and older?
2. How do temperature fluctuations affect their health and perceived comfort?
3. Are the SENIOR COMFORT Metrics 2013 better indicators than the ASHRAE-55 2010 Standards for examining temperatures and their effects on the health and perceived indoor thermal comfort of older adults?

Primary Research Hypotheses

1. More-stable indoor thermal conditions in relation to those outlined by ASHRAE-55 2010 are more strongly correlated to the health and perceived comfort of older

   adults living in a public-housing complex in North Phoenix.

2. Higher temperatures in relation to those outlined by ASHRAE-55 2010 for summer conditions represent a more-accurate threshold that better meets the needs of older adults living in a public-housing complex in North Phoenix.
3. The SENIOR Comfort Metrics are better predictors for assessing indoor residential temperatures and their effects on the actual health and perceived comfort of older adults living in a public-housing complex in North Phoenix.

Subquestions and Hypotheses

Sub-questions were developed to address more-specific correlations among the variables outlined in the conceptual model (Tables 9-11).

Table 9
Temperature Variability

Question	Hypothesis
How does age and gender affect through thermostat manipulation or other activities thermal variability?	Older adults depending on their may manipulate more or less their thermostat or conduct other activities that will increase thermal variability.
Do building attributes, including location and orientation, influence indoor thermal variability?	South- and west-oriented units are more directly exposed to solar radiation; as a result, these units will experience more/greater temperature fluctuations, increasing frequency of health and thermal-comfort problems. A. Floor level B. Orientation C. Wing
Does resident behavior influence indoor unit temperature variability?	Residents with varied physical-activity levels will manipulate HVAC controls or window operation more often, resulting in more-frequent indoor temperature fluctuation. A. Activity levels B. HVAC manipulation
How do temperature variations affect health and perceived comfort of older adults?	More-stable indoor thermal conditions in relation to those outlined by ASHRAE-55 2010 in its temperature variability section will increase health and perceived comfort. A. Less overall sleep problems

	B. Less physical injuries C. Perceptions of thermal comfort D. Less muscular and joint pains E. Better mood
How do temperature variations affect health and perceived comfort of older adults?	More-stable indoor thermal conditions in relation to those outlined by SENIOR COMFORT Metrics 2013 in its temperature variability section will increase health and perceived comfort. A. Less overall sleep problems B. Less physical injuries C. Perceptions of thermal comfort D. Less muscular and joint pains E. Better mood
Do units with frequent temperature variations experience extreme temperature values?	Frequent temperature variations correlate with extreme temperature values.

Table 10
Temperature Extremes

Question	Hypothesis
Do building attributes, including location and orientation, influence indoor thermal extremes?	South- and west-oriented units will be more directly exposed to solar radiation; as a result, these units will experience more and greater temperature extremes, therefore increasing the frequency of health and thermal-comfort related problems. A. Floor level B. Orientation C. Wing
Does resident behavior influence indoor unit temperature extremes?	Residents who maintain varied levels of physical activity will manipulate HVAC controls or window operation more often, resulting in more-frequent indoor temperature extremes. A. Activity levels B. HVAC manipulation
How do temperature extremes affect the health and perceived comfort of older adults?	More stable indoor thermal conditions in relation to those outlined by ASHRAE-55 2010 in its temperature extremes section will increase health and perceived comfort. A. Less overall sleep problems B. Less physical injuries C. Perceptions of thermal comfort D. Less muscular and joint pains E. Better mood

Table 11
Better Indicators

Question	Hypothesis
Are the SENIOR COMFORT Metrics 2013 better predictors than those outlined by ASHRAE-55 2010 for examining indoor thermal attributes (temperature variability, high, lows and relative humidity) and its effects on the actual health and perceived comfort of older adults at SSM?	The SENIOR COMFORT Metrics 2013 temperature variability allowances better fit older adults' thermal preferences; this will allow for a more thermally stable, healthier, and more comfortable indoor environment, therefore representing a better metric than ASHRAE-55 2010.

Statistics

The following section describes in detail the various statistical tests, used to determine possible correlations between the different predictors, moderating factors, mediating factors, and outcomes. These tests and their results will be used to discuss how temperature is affecting the health and comfort of older adults at Sunnyslope.

ASHRAE-55 Standards, SENIOR COMFORT Metrics, and SSM Thermal Conditions

The ASHRAE-55 2010 Standards, the SENIOR COMFORT Metrics 2013, and the actual indoor thermal conditions at SSM were studied and correlated, to identify: 1) typical and preferred thermal conditions among older adults at SSM; and 2) variations during the day between their indoor thermal preferred and chosen conditions and those recommended as healthy indoor thermal conditions by ASHRAE-55 2010. These correlations will allow for a partial determination as to whether or not this standard represents the preferred thermal conditions for older adults in hot, arid climates.

The SENIOR COMFORT metrics will be subjected to the same protocol, to determine if these metrics are better predictors for determining older adult indoor thermal preferences.

1. **ASHRAE-55 2010 Metrics of Temperature Extremes and Variability:**

   To examine the influence of temperature values which are either too high (i.e., greater than 83°F) or too low (i.e., less than 73°F) from the health outcomes, an analysis of covariance was computed. The independent variables were computed by setting the average temperature values between 83 and 73°F to 0 and by average temperature values that are too high or too low to 1.
   The standard deviation of the temperature values for each individual value was entered as a covariate, and each outcome variable was used as the dependent variable. This analysis will indicate whether or not extreme temperature values and temperature variability influence the health outcomes, taking into account the relationship between extreme temperature values and temperature variability.

   To examine the influence of thermal variability on the health outcomes, a correlation analysis was computed. The frequency with which the temperature values varied by more than 6°F over four hours was correlated with the health outcomes. I used a previous analysis of the relationship among the predictor variables to determine the frequency with which the different allowable thermal variability metrics are related, whether or not they should be treated independently, and whether or not the four-hour metric represents all three metrics.

2. **SENIOR COMFORT Metrics of Temperature Extremes:**

To examine the influence of temperature values that are either too high (i.e., >83°F) or too low (i.e., <76°F) on the health outcomes, an analysis of covariance was computed. The independent variables were computed by setting the average temperature values between 83 and 76 to 0 and average temperature values that are too high or too low to 1. The standard deviations of the temperature values for each individual were entered as covariates, and each outcome variable was used as the dependent variable. The analysis of these calculations will indicate whether or not extreme temperature values and temperature variability influence the health outcomes, while also taking into account the relationship between extreme temperature values and temperature variability.

3. **SENIOR COMFORT Metrics of Temperature Variability:**

To examine the influence of thermal variability on health outcomes, I conducted a correlation analysis of the frequency with which the temperature values varied by more than 3°F over three hours with health outcomes. I used a previous analysis of the relationship among the predictor variables to determine the frequency with which the different allowable thermal variability metrics related, whether or not they should be treated independently, and whether or not the three-hour metric provides a satisfactory representation of all three metrics.

This analysis was conducted with all data, as a conglomerate of all of the collected thermal data for five days.

Correlations between Indicators

The main objective of these analyses was to identify significant correlations between indoor absolute temperatures and temperature variability and to determine their potential effects on actual health and perceptions of older adults. The following analyses among predictors were implemented to obtain desired information:

1. To examine interrelationships among the predictors, I computed the correlation among predictors. The purpose of this set of tests was to better understand the relationship among predictors, moderators, and mediating factors.
2. Outcome variables originated from self-report questionnaires; during data preparation, I organized the instruments into scales. Outcomes were correlated to the SENIOR COMFORT Metrics 2013 thresholds, ASHRAE-55 2010 thresholds, and temperature parameters.
3. I compared the SENIOR COMFORT Metrics to ASHRAE-55 2010, to determine which metric best predicts the most-adequate thermal conditions for older adults.

Statistical Test Matrices

Table 12
Thermal Variability, Age, and Gender

Question	Test
1.0 How does age and gender affect thermal variability?	PEARSON's Correlation: Correlate temperature variability with age and gender
	SENIOR Comfort _30_min VS Q1 SENIOR Comfort _1_hr VS Q1 SENIOR Comfort _3_hr VS Q1 SENIOR Comfort _30_min VS Q2 SENIOR Comfort _1_hr VS Q2 SENIOR Comfort _3_hr VS Q2
	ASHRAE_15_min VS Q1 ASHRAE_30_min VS Q1 ASHRAE_1_hr VS Q1 ASHRAE_2_hr VS Q1 ASHRAE_4_hr VS Q1 ASHRAE_15_min VS Q2 ASHRAE_30_min VS Q2 ASHRAE_1_hr VS Q2 ASHRAE_2_hr VS Q2 ASHRAE_4_hr VS Q2 SD_Temperature_Composite VS Q1 SD_Temperature_Composite VS Q2

Table 13
Thermal Variability and Building Attributes

Question	Test
1.1 Do building attributes, including location and orientation, influence indoor thermal variability?	ANOVA: Compare temperature variability allowances as outlined by ASHRAE-55 2010 and SENIOR COMFORT Metrics 2013 to actual variability count and frequencies per floor level, orientation, and wing
	SENIOR Comfort _30_min VS Floor SENIOR Comfort _1_hr VS Floor SENIOR Comfort _3_hr VS Floor ASHRAE_15_min VS Floor ASHRAE_30_min VS Floor ASHRAE_1_hr VS Floor ASHRAE_2_hr VS Floor ASHRAE_4_hr VS Floor
	SENIOR Comfort _30_min VS Orientation SENIOR Comfort _1_hr VS Orientation SENIOR Comfort _3_hr VS Orientation ASHRAE_15_min VS Orientation ASHRAE_30_min VS Orientation ASHRAE_1_hr VS Orientation ASHRAE_2_hr VS Orientation ASHRAE_4_hr VS Orientation SENIOR Comfort _30_min VS Wing SENIOR Comfort _1_hr VS Wing SENIOR Comfort _3_hr VS Wing ASHRAE_15_min VS Wing ASHRAE_30_min VS Wing ASHRAE_1_hr VS Wing ASHRAE_2_hr VS Wing ASHRAE_4_hr VS Wing

Table 14
Thermal Variability and Behavior

Question	Test
1.2 Does resident behavior influence indoor unit temperature variability?	PEARSON's Correlation: Correlate temperature variability exceeding allowances, as outlined by ASHRAE-55 2010 and the SENIOR COMFORT Metrics 2013 against the self-reported activity levels and HVAC manipulation
	SENIOR Comfort _30_min VS Activity_Composite SENIOR Comfort _1_hr VS Activity_Composite SENIOR Comfort _3_hr VS Activity_Composite ASHRAE_15_min VS Activity_Composite ASHRAE_30_min VS Activity_Composite ASHRAE_1_hr VS Activity_Composite ASHRAE_2_hr VS Activity_Composite ASHRAE_4_hr VS Activity_Composite SENIOR Comfort _30_min VS Q80 SENIOR Comfort _1_hr VS Q80 SENIOR Comfort _3_hr VS Floor ASHRAE_15_min VS Q80 ASHRAE_30_min VS Q80 ASHRAE_1_hr VS Q80 ASHRAE_2_hr VS Q80 ASHRAE_4_hr VS Q80

Table 15
Thermal Variability, Health, and Perceived Comfort

Question	Test
1.3 How do temperature variations affect the health and perceived comfort of older adults?	1.3.1 PEARSON's Correlation: Correlate temperature variability exceeding the ASHRAE-55 2010 temperature variation allowances against the count of overall perceptions of thermal comfort, muscular and joint pains, sleep problems, count of physical injuries, and mood
	ASHRAE_15_min VS Perception_of_Thermal_Composite ASHRAE_30_min VS Perception_of_Thermal_Composite ASHRAE_1_hr VS Perception_of_Thermal_Composite ASHRAE_2_hr VS Perception_of_Thermal_Composite ASHRAE_4_hr VS Perception_of_Thermal_Composite
	ASHRAE_15_min VS Pain_Composite ASHRAE_30_min VS Pain_Composite

	ASHRAE_1_hr VS Pain_Composite ASHRAE_2_hr VS Pain_Composite ASHRAE_4_hr VS Pain_Composite
	ASHRAE_15_min VS Sleep_Patterns_Composite ASHRAE_30_min VS Sleep_Patterns_Composite ASHRAE_1_hr VS Sleep_Patterns_Composite ASHRAE_2_hr VS Sleep_Patterns_Composite ASHRAE_4_hr VS Sleep_Patterns_Composite
	ASHRAE_15_min VS Physical_Injuries_Composite ASHRAE_30_min VS Physical_Injuries_Composite ASHRAE_1_hr VS Physical_Injuries_Composite ASHRAE_2_hr VS Physical_Injuries_Composite ASHRAE_4_hr VS Physical_Injuries_Composite
	ASHRAE_15_min VS Mood_Composite ASHRAE_30_min VS Mood_Composite ASHRAE_1_hr VS Mood_Composite ASHRAE_2_hr VS Mood_Composite ASHRAE_4_hr VS Mood_Composite
	1.3.2 PEARSON's Correlation: Correlate temperature variability exceeding the SENIOR COMFORT Metrics 2013 temperature variation allowances against the count of overall perceptions of thermal comfort, muscular and joint pains, sleep problems, physical injuries, and mood
	SENIOR Comfort _30_minVS Perception_of_Thermal_Composite SENIOR Comfort _1_hr VS Perception_of_Thermal_Composite SENIOR Comfort _3_hr VS Perception_of_Thermal_Composite
	SENIOR Comfort _30_min VS Pain_Composite SENIOR Comfort _1_hr VS Pain_Composite SENIOR Comfort _3_hr VS Pain_Composite
	SENIOR Comfort _30_min VS Sleep_Patterns_Composite SENIOR Comfort _1_hr VS Sleep_Patterns_Composite SENIOR Comfort _3_hr VS Sleep_Patterns_Composite
	SENIOR Comfort _30_min VS Physical_Injuries_Composite SENIOR Comfort _1_hr VS Physical_Injuries_Composite SENIOR Comfort _3_hr VS Physical_Injuries_Composite SENIOR Comfort _30_min VS Mood_Composite SENIOR Comfort _1_hr VS Mood_Composite SENIOR Comfort _3_hr VS Mood_Composite

Table 16
Temperature Variability and Temperature Extremes

Question	Test
1.4 Do units with frequent temperature variations experience extreme temperature values?	PEARSON's Correlation: Correlate temperature variability with temperature extremes
	ASHRAE_15_min VS Max_Temperature_Composite ASHRAE_30_min VS Max_Temperature_Composite ASHRAE_1_hr VS Max_Temperature_Composite ASHRAE_2_hr VS Max_Temperature_Composite ASHRAE_4_hr VS Max_Temperature_Composite SENIOR Comfort _30_min VS Max_Temperature_Composite SENIOR Comfort _1_hr VS Max_Temperature_Composite SENIOR Comfort _3_hr VS Max_Temperature_Composite
	ASHRAE_15_min VS Min_Temperature_Composite ASHRAE_30_min VS Min_Temperature_Composite ASHRAE_1_hr VS Min_Temperature_Composite ASHRAE_2_hr VS Min_Temperature_Composite ASHRAE_4_hr VS Min_Temperature_Composite SENIOR Comfort _30_min VS Min_Temperature_Composite SENIOR Comfort _1_hr VS Min_Temperature_Composite SENIOR Comfort _3_hr VS Min_Temperature_Composite ASHRAE_15_min VS SD_Temperature_Composite ASHRAE_30_min VS SD_Temperature_Composite ASHRAE_1_hr VS SD_Temperature_Composite ASHRAE_2_hr VS SD_Temperature_Composite ASHRAE_4_hr VS SD_Temperature_Composite

Table 17
Temperature Extremes and Building Attributes

Question	Test
2.0 Do building attributes, including location and orientation, influence indoor thermal extremes?	ANOVA: Compare temperature extreme allowances as outlined by ASHRAE-55 2010 and SENIOR COMFORT Metrics 2013 to actual variability count and frequencies per orientation, wing and floor level
	1. Max_Temperature_Composite VS Floor 2. Min_Temperature_Composite VS Floor 3. Temperature_Composite VS Floor
	1. Max_Temperature_Composite VS Orientation 2. Min_Temperature_Composite VS Orientation 3. Temperature_Composite VS Orientation 1. Max_Temperature_Composite VS Wing 2. Min_Temperature_Composite VS Wing 3. Temperature_Composite VS Wing

Table 18

Question	Test
2.1 Does resident behavior influence indoor unit temperature extremes?	PEARSON's Correlation: Correlate temperature extremes exceeding allowances as outlined by ASHRAE-55 2010 and SENIOR COMFORT Metrics 2013 against the self-reported activity levels and HVAC manipulation
	1. Max_Temperature_Composite VS Activity_Composite 2. Min_Temperature_Composite VS Activity_Composite 3. Temperature_Composite VS Activity_Composite 1. Max_Temperature_Composite VS Q80 2. Min_Temperature_Composite VS Q80 3. Temperature_Composite VS Q80

Table 19
Temperature Extremes and Perceived Comfort

Question	Test
2.2 How do temperature extremes affect the health and perceived comfort of older adults?	PEARSON's Correlation:Temperature extremes exceeding the ASHRAE-55 2010 temp variation allowances will be correlated against the count of overall sleep problems, count of physical injuries, perceptions of thermal comfort, muscular and joint pains and mood.
	1. MAX_ASHRAE VS Perception_of_Thermal_Composite 2. MIN_ASHRAE VS Perception_of_Thermal_Composite 1. MAX_SENIOR Comfort VS Perception_of_Thermal_Composite 2. MIN_SENIOR Comfort VS Perception_of_Thermal_Composite 1. SD_Temperature_Composite VS Perception_of_Thermal_Composite 1. MAX_ASHRAE VS Pain_Composite 2. MAX_ASHRAE VS Pain_Composite 1. MAX_SENIOR Comfort VS Pain_Composite 2. MIN_SENIOR Comfort VS Pain_Composite 1. SD_Temperature_Composite VS Pain_Composite
	1. MAX_ASHRAE VS Sleep_Patterns_Composite 2. MAX_ASHRAE VS Sleep_Patterns_Composite 1. MAX_SENIOR Comfort VS Sleep_Patterns_Composite 2. MIN_SENIOR Comfort VS Sleep_Patterns_Composite 1. SD_Temperature_Composite VS Sleep_Patterns_Composite 1. MAX_ASHRAE VS Physical_Injuries_Composite 2. MAX_ASHRAE VS Physical_Injuries_Composite 1. MAX_SENIOR Comfort VS Physical_Injuries_Composite 2. MIN_SENIOR Comfort VS Physical_Injuries_Composite 1. SD_Temperature_Composite VS Physical_Injuries_Composite 1. MAX_ASHRAE VS Mood_Composite 2. MAX_ASHRAE VS Mood_Composite 1. MAX_SENIOR Comfort VS Mood_Composite 2. MIN_SENIOR Comfort VS Mood_Composite 1. SD_Temperature_Composite VS Mood_Composite

Table 20
Better Indicators

Question	Hypothesis
3.0 Are SENIOR COMFORT Metrics 2013 better predictors than those in ASHRAE-55 2010, for examining indoor thermal attributes (temperature variability, highs, lows, relative humidity) and their effects on actual health and perceived comfort of older adults at Sunnyslope?	SENIOR COMFORT Metrics 2013 temperature variability allowances better fit the needs of older adults' thermal preferences, therefore allowing for a more thermally stable, healthier, and more comfortable indoor environment; therefore the SENIOR COMFORT Metrics 2013 represent a better metric than ASHRAE-55 2010.

Chapter 4

RESULTS

Descriptive Statistics

Table 21 displays the descriptive statistics of the study variables, including mean, standard deviation, maximum, and minimum. From the total sample (*n*=76), 71.4% of participants were women and 28.6% were men. This breakdown reflects national trends, which indicate that women have a longer life expectancy. The mean age was 74.21, with a minimum age of 62, a maximum of 92, and a standard deviation of 7.94 years.

Table 21
Descriptive Statistics of Study Variables (*n*=76)

Composite	Mean	SD	Minimum	Maximum
Age	74.21	7.94	62	92
Activity	2.35	0.77	1.09	4.09
Perception of Thermal	5.77	1.17	2.5	7
Pain	0.38	0.33	0	1
Sleep Patterns	0.02	0.80	-0.92	1.67
Physical Injuries	0	0.51	-0.74	1.42
Mood Composite	2.09	0.75	1	3.86
Max Temperature	82.39	3.03	76.7	92.14
Min Temperature	75.51	3.33	66.71	81.8
SD Temperature	1.45	0.75	0.55	3.62

The maximum temperature was recorded at 92.14°F, while the minimum was 76.72°F, with a mean of 82.39°F and a standard deviation of 3.03°F. The minimum temperature was recorded at 66.71°F, while the maximum was 81.80°F, with a mean of 75.51°F and a standard deviation of 3.33°F. The difference between highs and lows within the Maximum and Minimum Temperature Composites is 15.44°F and 15.09°F, respectively, indicating high and low temperatures follow the same temperature trend changes. The standard deviation between the two composites also shows similar values.

Table 22 reports the distribution of residents within the residential complex. A total of 40.3% of the 76 participants live on the second floor; 59.7% are evenly divided between the first and third floors. Distribution between south-facing and north-facing apartments is highly similar, with 49.4% living on the south side and 50.6% on the north side; 54.5% live in the west wing, while 45.5% live in the east wing. Finally, 89.6% do not manipulate their thermostat to control temperatures.

Table 22
Population Distribution within Building Complex (*n*=76)

Gender	Percentage
Male	28.6%
Female	71.4%
HVAC (Thermostat) manipulation	
Yes	10.4%
No	89.6%
Floor level	
First	29.9%
Second	40.3%
Third	29.8%
Orientation	
North	49.4%
South	50.6%
Wing	
East	45.5%
West	54.5%

Correlation between Indoor Thermal Variability and Age and Gender

Table 23 displays correlation results between indoor thermal variability and age. The computations were conducted in relation to SENIOR Comfort METRICS 2013 and ASHARE-55 2010 standards, as well as in relation to specific temperature-variability allowances during different timeframes. Age does not correlate with thermal variability.

Table 23
Correlation between Indoor Thermal Variability and Age (*n*=76)

	Age	
Metric	r	*p*-value
SENIOR COMFORT Metrics 2013		
30 minutes	-0.057	0.626
1 hour	-0.144	0.214
3 hours	-0.120	0.303
ASHRAE-55 2010 Standards		
15 minutes	0.004	0.972
30 minutes	-0.002	0.987
1 hour	-0.052	0.656
2 hours	-0.183	0.114
4 hours	-0.146	0.211
Temperature Composite Standard Deviation	-0.124	0.284

*p<.05

Table 24 demonstrates differences by gender, indicating whether or not those differences affect thermal variability in various degrees. These comparisons were computed against the SENIOR Comfort METRICS 2013 and the ASHRAE-55 2010 Standard. Gender does not appear to affect the allowable rate of thermal variability. However, at the two-hour threshold in relation to the ASHRAE-55 2010 Standard, gender is significant (*p*-value of *p*=0.01).

Table 24
Indoor Thermal Variability by Gender ANOVA (*n*=76)

	Gender		
	df	F	*p*-value
SENIOR COMFORT Metrics 2013			
30 minutes	75	0.063	0.802
1 hour	75	2.431	0.123
3 hours	75	0.493	0.485
ASHRAE-55 2010 Standards			
15 minutes	75	2.126	0.149
30 minutes	75	3.052	0.085
1 hour	75	3.747	0.057
2 hours	75	6.719*	0.011
4 hours	74	2.431	0.123
Temperature Composite Standard Deviation	75	0.134	0.715

* $p<.05$

Thermal Variability by Floor

Table 25 displays the thermal differences between floors. Floor level does not seem to correlated to the allowable rate of thermal variability for the SENIOR COMFORT METRICS or ASHRAE-55 2010 Standards. However, at the 15- and 30-minute thresholds, per the ASHRAE-55 2010 Standard, the floor does make a difference, with a

p-value of $p=0.05$ and $p=0.048$. A subsequent post hoc test identified the specific difference by space; these results, shown in Table 24, indicate differences between the first and second floors, with a mean difference of $d=1.0547$ and significance of $p=0.045$.

Table 25
Indoor Thermal Variability by Gender ANOVA (*n*=76)

	Floor		
	df	F	*p*-value
SENIOR COMFORT Metrics 2013			
30 minutes	75	0.516	0.599
1 hour	75	0.907	0.408
3 hours	75	0.335	0.716
ASHRAE-55 2010 Standards			
15 minutes	75	3.094*	0.051
30 minutes	75	3.172*	0.048
1 hour	75	1.942	0.151
2 hours	75	0.195	0.823
4 hours	74	1.025	0.364

*p<.05

Table 26
Post-Hoc Indoor Thermal Variability by Floor, ANOVA (*n*=76)

	Floor			
	Floor level	Floor Level	Mean Difference	Significance
ASHRAE-55 2010				
30 minutes	1	2	1.05470*	0.045

* p < .05

Thermal Variability by Orientation

Table 27 displays the difference between the SENIOR Comfort METRICS and the ASHRAE-55 2010 Standards, by direction the unit is facing and indicates whether the orientation of the units affects thermal variability. Orientation appears to affect the allowable rate of thermal variability significantly for either standard at the one-hour threshold or less. Based on the allowable temperature rate of change of the SENIOR

COMFORT METRICS 2013, temperatures varied significantly between at least two orientations at both the 30-minute threshold, with a *p*-value of *p*=0.031, and the 60-minute threshold, with a *p*-value of *p*=0.039. The same was observed for the ASHRAE-55 2010 Standards at the 60-minute threshold, with a *p*-value of *p*=0.041.

Table 27
Indoor Thermal Variability by Orientation, ANOVA (*n*=76)

	Orientation		
	df	F	*p*-value
SENIOR COMFORT Metrics 2013			
30 minutes	75	4.842*	0.031
1 hour	75	4.405*	0.039
3 hours	75	0.865	0.355
ASHRAE-55 2010 Standards			
15 minutes	75	3.517	0.065
30 minutes	75	3.801	0.055
1 hour	75	4.327*	0.041
2 hours	75	0.799	0.374
4 hours	74	0.474	0.494

* $p < .05$

Thermal Variability by Wing

Table 28 displays the difference between the SENIOR COMFORT Metrics 2013 and the ASHRAE-55 2010 Standards, by the building wings in which the units are located and indicates whether or not differences by wing affected thermal variability. Wing location appears to be significant and impacts overall variability per the SENIOR COMFORT Metrics, but only at the 3 hour threshold and near-significant at the 4 hours threshold as outlined by ASHRAE 55-2010. Based upon those thresholds, temperature variability allowances were exceeded. Results show significant *p*-value of *p*=0.025 at the 3-hour threshold.

Table 28
Indoor Thermal Variability by Wing (*n*=76)

	Wing		
	df	F	*p*-value
SENIOR COMFORT Metrics 2013			
30 minutes	75	0.857	0.358
1 hour	75	1.255	0.266
3 hours	75	5.228*	0.025
ASHRAE-55 2010 Standards			
15 minutes	75	0.053	0.819
30 minutes	75	0.215	0.644
1 hour	75	0.597	0.442
2 hours	75	2.039	0.158
4 hours	74	3.432	0.068

* $p < .05$

Correlation between Indoor Thermal Variability and Activity Level

Table 29 indicates the levels of correlation between activity level—personal adjustments such as manipulation of the thermostats or windows/doors—to temperature variability. This table reveals no correlation between activity level and temperature variability outlined by the SENIOR COMFORT METRICS and the ASHRAE-55 2010 Standards.

Table 29
Correlation between Indoor Thermal Variability and Activity Level (*n*=76)

	Activity Level	
	r	*p*-value
SENIOR COMFORT Metrics 2013		
30 minutes	0.037	0.752
1 hour	0.012	0.916
3 hours	0.147	0.205
ASHRAE-55 2010 Standards		
15 minutes	-0.075	0.522
30 minutes	-0.107	0.358
1 hour	-0.123	0.290
2 hours	-0.027	0.818
4 hours	0.083	0.479

* $p<.05$

Indoor Thermal Variability by HVAC Manipulation

Table 30 displays the differences between the SENIOR COMFORT METRICS and the ASHRAE-55 2010 Standards and indicates whether differences by HVAC manipulation affect thermal variability. Based on the data, HVAC manipulation produced a significant effect at greater periods of time. Based on the SENIOR COMFORT METRICS, temperature variability allowances at the 3-hour threshold differed by HVAC manipulation (p=0.012). Similar results were observed with the ASHRAE-55 2010 Standards at the 4-hour threshold (p=0.050). No other thresholds differed significantly by HVAC manipulation.

Table 30
Indoor Thermal Variability by HVAC Manipulation, ANOVA (*n*=76)

	HVAC manipulation		
	df	F	*p*-value
SENIOR COMFORT Metrics 2013			
30 minutes	75	0.030	0.865
1 hour	75	0.096	0.758
3 hours	75	6.715*	0.012
ASHRAE-55 2010 Standards			
15 minutes	75	0.229	0.633
30 minutes	75	0.271	0.604
1 hour	75	0.243	0.623
2 hours	75	1.003	0.320
4 hours	74	3.971*	0.050

* $p<.05$

Indoor Thermal Variability and Perceived Comfort

Table 31 displays the correlation levels between the SENIOR COMFORT Metrics 2013 thermal variability allowances, the ASHRAE-55 2010 Standards recommended thermal variability allowances, and the various outcome measures: perception of comfort (Perception TC) and reported health, pain, sleep patterns, injuries, and mood. The correlation between thermal variability and these measures for both metric systems is insignificant. There is a near-marginal significant correlation between the SENIOR COMFORT Metrics 2013 30-minute threshold and the Perception of Thermal Comfort with a *p*-value of p=0.076.

Table 31

Correlation Between Indoor Thermal Variability and Perceived Comfort and Reported Health (*n*=76)

	Perception TC		Pain		Sleep Patterns		Injuries		Mood	
	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value
SENIOR COMFORT Metrics 2013										
30 minutes.	0.21	0.076	0.028	0.807	0.079	0.499	0.038	0.744	0.15	0.208
1 hour	0.19	0.098	0.028	0.809	0.071	0.545	0.075	0.517	0.2	0.092
3 hours	0.11	0.339	0.025	0.829	-0.18	0.129	-0.06	0.603	0.18	0.115
ASHRAE-55 2010 Standards										
15 min.	0.16	0.161	-0.01	0.909	-0.01	0.91	0.135	0.247	0.12	0.304
30 min.	0.17	0.154	-0.05	0.694	-0.04	0.706	0.093	0.423	0.11	0.369
1 hour	0.15	0.206	< -0	0.982	-0.05	0.697	0.148	0.202	0.13	0.287
2 hours	0.1	0.379	-0.07	0.537	-0.13	0.272	-0.08	0.509	0.12	0.321
4 hours	0.02	0.873	-0.04	0.756	-0.18	0.128	-0.11	0.333	0.17	0.16

* $p < .05$

Indoor Thermal Variability and Temperature Extremes

Table 32 shows correlation levels between the thermal variability allowances of SENIOR COMFORT METRIC 2013 and the ASHRAE-55 2010 Standards, and the minimum and maximum composites. Correlations between the minimum temperature composite and the two metrics were highly significant for every threshold, which indicates that temperature variability systematically affects low indoor temperatures. The maximum temperature composite strongly correlated to the SENIOR COMFORT Metrics at the 3-hour threshold and the ASHRAE at thresholds of 15 minutes, 30 minutes, and 1 hour. All correlations were nearly absolute.

Table 32
Correlation between Indoor Thermal Variability & Temperature Extremes (*n*=76)

	Min Temp Composite		Max Temp Composite	
	r	*p*-value	r	*p*-value
SENIOR COMFORT Metrics 2013				
30 minutes	-0.344*	0.002	0.183	0.113
1 hour	-0.441*	< 0.00	0.203	0.078
3 hours	-0.514*	< 0.00	0.242*	0.035
ASHRAE-55 2010 Standards				
15 minutes	-0.214	0.063	0.403*	< 0.00
30 minutes	-0.227*	0.049	0.353*	0.002
1 hour	-0.377*	0.001	0.303*	0.008
2 hours	-0.468*	< 0.000	0.124	0.288
4 hours	-0.527*	< 0.000	0.120	0.305

* p<.05

Temperature Extremes and Building Attributes

Table 33 demonstrates differences among the minimum, maximum, temperature (mean) composites, and building attributes (floor, orientations, and wings). The differences between the wings and their relation to extremes, average, or minimum temperatures were all insignificant. Maximum temperatures, on the other hand, highly relate to floor level, with a *p*-value of *p*=0.018, and to south/north orientation, with an even stronger correlation of *p*=0.004. The ANOVA test is limited and provides no further information as to which orientation or floor level is most affected by high temperature; thus a post-hoc Tukey HSD test was conducted (results in Table 33).

Table 33
Extreme Temperatures by Floor, Orientation, and Wing, ANOVA (*n*=76)* *p* < .05

	Floor		
	df	F	*p*-value
Min Temperature Composite	75	1.236	0.297
Max Temperature Composite	75	4.273*	0.018
Temperature Composite	75	2.259	0.112
	Orientation		
	df	F	*p*-value
Min Temperature Composite	75	0.777	0.381
Max Temperature Composite	75	8.588*	0.004
Temperature Composite	75	3.253	0.075
	Wing		
	df	F	*p*-value
Min Temperature Composite	75	0.000	0.988
Max Temperature Composite	75	1.942	0.168
Temperature Composite	75	0.650	0.423

Table 34 shows the differences among all specific groups tested in Table 32. The largest differences between maximum temperatures are between the first and third floors, the second and third floors and the third, second and first floors. The common factor is the third floor, the floor most affected by high temperatures.

Table 34, TUKEY HSD (*n*=76)

Dependent Variable	Floor Levels		Mean Dif.	*p*-value
Max Temperature Composite	1	2	-.0761	.9950
		3	-2.18868*	.0359
	2	1	.0761	.9950
		3	-2.11260*	.0291
	3	1	2.18868*	.0359
		2	2.11260*	.0291
Min Temperature Composite	1	2	-.1018	.9932
		3	-1.3753	.3518
	2	1	.1018	.9932
		3	-1.2735	.3587
	3	1	1.3753	.3518
		2	1.2735	.3587
Temperature Composite	1	2	-.2205	.9398
		3	-1.3931	.1301
	2	1	.2205	.9398
		3	-1.1726	.1893
	3	1	1.3931	.1301
		2	1.1726	.1893

* p<.05

Temperature Extremes and Behavior

Table 35 demonstrates relationships between extreme temperatures and activity levels, and between extreme temperatures and manipulations of the HVAC unit to control temperatures. No correlations were found.

Table 35
Temperature Extremes and Activity Behavior, (*n*=76)

	Activity Composite		
	r	*p*-value	
Min Temperature Composite	0.000	0.999	
Max Temperature Composite	0.155	0.180	
Temperature Composite	0.130	0.263	
	HVAC manipulation		
	df	F	*p*-value
Min Temperature Composite	75	0.745	0.391
Max Temperature Composite	75	0.495	0.484
Temperature Composite	75	0.130	0.720

* p<.05

Temperature Extremes and Perceived Comfort and Reported Health

Table 36 shows correlations between extreme temperatures and standard deviation of the temperature composite, related to outcome composites. No outcomes were correlated to the SENIOR COMFORT thresholds. However, strong correlations exist between the ASHRAE Standards minimum summer temperature and injuries (*p*=0.024); the same for mood and ASHRAE minimum temperature thresholds (*p*=0.040). Temperature variability correlated to mood *p*=0.045).

Table 36

Correlation between Extreme Temperatures and Perceived Comfort and Reported Health (*n*=76)

	Perception		Pain		Sleep Patterns		Injuries		Mood	
	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value
SENIOR COMFORT Metrics										
Min	0.09	0.437	-0.06	0.581	-0.03	0.816	-0.027	0.819	0.08	0.494
Max	0.03	0.821	-0.08	0.52	-0.02	0.887	0.025	0.819	0.142	0.224
ASHRAE-55 2010 Standards										
Min	0.07	0.56	0.173	0.135	-0.08	0.509	0.259*	0.024	0.238*	0.04
Max	0.02	0.892	-0.02	0.874	0.023	0.845	-0.029	0.802	0.089	0.449

* $p < .05$

A complete summary of significant results, including corresponding questions and hypothesis are comprised in Appendix A.

Chapter 5

CONCLUSIONS AND DISCUSSION

Discussion of Results

“Thermal comfort, or the lack of it, is well understood to be one of the most significant restrictors to the health and general wellbeing of older people” (Novieto & Zhang, 2010). Novieto and Zhang’s argument gave root to this dissertation and nurtured its advance. Undoubtedly, too-low or too-high indoor temperatures affect, in different ways, the physical and intellectual functionality of older adults. Frumkin reported that heat stroke is one of the most common issues that older adults faced, explaining that temperatures exceeding 104°F can cause multiple body organ failures and increase the fatally rate in worse cases. (Frumkin, 2002). The Centers for Disease Control (CDC) support his position when they noted that “continued exposure to ambient heat close to body temperature (98.6ºF) contributes to a substantial number of deaths from hyperthermia, especially among elderly persons” (CDC, 2005).

Health risks related to heat stress are especially evident in Arizona, as reported in the CDC. “During 1979 and 2002, a total of 4,780 heat-related deaths in the United States were attributable to weather conditions and that, during 1993 and 2002, the incidence of such deaths was three to seven times greater in Arizona than in the United States overall” (CDC, 2005). Designing adequate guidelines for thermal comfort for all populations is crucial, especially for demographic groups such as older adults and children who lack the ability to regulate their body temperatures efficiently.

My collaborative research at Sunnyslope Manor in the City of Phoenix, while not conclusive and requiring more research, indicates that older adults seem to prefer slightly higher temperatures than those outlined in ASHRAE-55 2010. (ASHRAE-55, 2010). This conclusion which is not final was reached based on resulting descriptive information of existing thermal conditions at Sunnyslope Manor per apartment unit. These results are heavily supported by the literature which strengthens the argument that older adults seem to prefer slightly higher temperatures. It is important to understand that results are not conclusive and further and more extensive research is needed to solidify this claim.

The following discussion highlights the most significant findings of my research.

The SENIOR COMFORT Metrics 2013 calls for an increase on the recommended maximum and minimum temperature thresholds for indoor conditions for residences housing older adults. Currently, ASHRAE-55 2010 standards list thresholds for summer as a minimum of 73°F and a maximum of 81°F. The SENIOR COMFORT Metrics propose a minimum of 76°F and a maximum of 83°F, increases consistent with recommendations throughout literature. The mean minimum temperature at Sunnyslope was 75.51°F, and the mean maximum temperature was 82.39°F (Table 37).

Table 37
Temperature-Threshold Comparisons and Observed Temperatures

Item	ASHRAE-55 2010	SENIOR COMFORT Metrics	Sunnyslope Observed mean temperatures
Maximum	81	83	82.39
Minimum	73	76	75.51

As observed above, the temperature thresholds in the SENIOR COMFORT Metrics represent the actual conditions observed at Sunnyslope. This is a crucial and important recommendation that reinforces the SENIOR COMFORT Metrics' new proposed thresholds. Increasing these thresholds may afford residents a more-productive, pleasant, and healthier home environment and will enable designers and engineers to make better decisions when sizing mechanical systems, ventilation ducts, and calculating energy loads. Smaller mechanical-system sizes could be smaller, impacting operations, and lowering costs as well increasing comfort. The benefits of smaller systems are many, as they run for longer periods of time maintaining more-stable temperatures while avoiding spike energy usage or sudden increases or decreases of temperatures.

SENIOR COMFORT vs. ASHRAE at Sunnyslope

The SENIOR COMFORT Metrics 2013 maximum temperature recommended limit is 83°F; it was observed that 38% of all units experienced temperatures above the 83 degree threshold outlined by the SENIOR COMFORT Metrics 2013. The ASHRAE-55 2010 Standard maximum summer recommended indoor temperature is 81°F. It was observed that 63% of all residents' apartments recorded temperatures above that limit, 25% higher in relation to the SENIOR COMFORT Metrics. This observation is important, considering that the SENIOR COMFORT Metrics build off the concept of increasing the threshold recommended by ASHRAE-55 2010. These results were observed on descriptive statistical data and are inconclusive. However, these results show a strong correlation from Sunnyslope Manor residents preferring higher indoor thermal temperatures, again, a condition that is backed and supported by the literature. In this case, violations were lower for the SENIOR COMFORT Metrics, making this tool slightly more accurate for measuring actual temperature preferences for older adults at Sunnyslope Manor. This observation is unsurprising when you consider that, on multiple occasions during field visits, I noticed that some Sunnyslope residents did not run their air conditioning system at all. Although these cases were the minority, it may indicate that this sector of the population prefers higher indoor temperatures. An important factor to consider is that residents do not pay utilities; those costs are included in their fixed rent budget. Therefore, their personal energy costs did not influence their decision to use less or more electricity to cool their apartments.

Age, Gender and Thermal Variability

The mean age for all participating Sunnyslope Manor residents was 74, with a maximum age of 92, a minimum age of 62, with a standard deviation of 7.94 years. Regardless of the 30-year difference among many residents, age did not significantly affect thermal variability. Although over 70% (71.4%) of the resident were females, consistent with national trends, gender did not make an important difference. At the two-hour threshold, as outlined by ASHRAE-55 2010, results produced a p-value of p=0.01 which is very significant. Nonetheless, the result is inconclusive and only indicates that residents manipulate more their mechanical systems, windows, or doors, thus increasing indoor thermal variability. Table A1 summarizes whether the hypothesis is supported or not for this test.

Floor Level and Thermal Variability

The Sunnyslope Manor Housing Project has only three floor levels, which limits testing and comparing trends in other floors, especially those in the middle. The analysis of variance conducted, using on the SENIOR COMFORT Metrics and the ASHRAE-55 2010 thresholds, yielded little significant results. At 30 minutes per ASHRAE-55 2010 Standards, it was observed that thermal variability was significant. A second post-hoc test was performed to identify the floors experiencing the most changes. Test results show that the second floor experienced greater thermal variability, a result confirmed through a simple standard deviation calculation per floor level.

These results were surprising. I expected that the third floor, being the most exposed to the elements, would experience the most temperature changes and thermal variability. I also hypothesized that the first floor would experience greater thermal variability, not because of its exposure to the elements but because is the most-trafficked floor, exposing it to more-frequent air moment which would allow for more thermal exchanges in a space. It is unclear why the second floor was the most affected, perhaps because changes in third floor impact the second and traffic and constant air changes in public areas in the first floor. There is no evidence that proves one or the other argument and, considering that we only have one single middle floor, it is impossible to compare to other floors and draw conclusions. Table A2 summarizes whether the hypothesis is supported or not for this test.

Orientation Thermal Variability

Orientation greatly impacts thermal variability. The location of east or west wings did not make a difference, however north and south orientations showed strong correlations with thermal variability for both metrics being examined in this study. According to the SENIOR COMFORT Metrics at the 30- and 60-minute threshold, variability was very significant, possibly because these metrics are slightly more stringent, allowing for less variability to define adequate thermal comfort for older adults. On the other hand, the ASHRAE Standards test results show one single significant threshold at the 60-minute threshold. These results are consistent with expectations that the ASHRAE Standard allows more room for greater variability.

These results reveal much about the periods of time when thermal variability takes place—within the first hour. The ASHRAE Standard threshold at 15 minutes recorded a near-significant *p*-value which further indicates that thermal variability occurs when tested in shorter periods of time. This result might also mean that temperature cycles occur every three to four hours in this type of dwelling units at Sunnyslope. Table A2 summarizes whether the hypothesis is supported or not for this test.

Activity Level and Thermal Variability

Although it is well understood that physical activity decreases with age (Havenith, 2001; McGeehin & Mirabelli, 2001), the extent of thermal variability on activity levels remains unclear and uncertain. It might be more an issue of thermal

comfort and not so much one that affects activity levels as observed at Sunnyslope. According to the literature, older adults have more difficulties regulating their core-body temperatures and experience a delayed skin-thermal sensation when temperature changes occur
(Tochihara, Tadakatsu, Nagai, Tokuda, & Kawashima, 1993). All these conditions lead me to hypothesize that thermal variability would affect activity levels. However, the correlations between the thresholds outlined by SENIOR COMFORT Metrics and the ASHRAE Standards, demonstrate that thermal variability did not affect activity levels.

Activity trends were also unclear and *p*-values for both metrics were inconsistent and show no trends that would indicate more significance at different time periods.
Low levels of indoor temperature inconsistencies at Sunnyslope Manor do not affect activity levels in older adults. These results open the door to other questions that could be addressed with more extensive research and a larger population sample. Table A3 summarizes whether the hypothesis is supported or not for this test.

HVAC Manipulation and Thermal Variability

Many factors affect thermal variability, especially in poorly insulated buildings, which could then affect behavior and the way users interact with mechanical systems when manipulating their thermostats. HVAC manipulation seems to be more prevalent at greater periods of time/thresholds outlined by both metrics. For the SENIOR COMFORT Metrics at the three-hour threshold, HVAC manipulation was very significant;

for the ASHRAE Standards at the four-hour threshold were very significant as well. For both metrics the trend is the same, HVAC manipulation occurs at greater periods of time which may reflect older adults needing to readjust settings at greater time intervals. It can also be the result of unwanted thermal changes due to heat transmission or heat loss, which would force users to adjust indoor-temperature settings. Table A3 summarizes whether the hypothesis is supported or not for this test.

Perceived Comfort and Indoor Thermal Variability

Perceived comfort is complicated to measure as it relates to specific indoor thermal changes over time. To measure perceived comfort, I conducted a Person correlation, testing the relationship between thermal variability as outlined by the ASHRAE Standards and the SENIOR COMFORT Metrics. All thresholds were tested in relation to Perception, Pain, Sleep Patterns, Injuries, and Mood. For both the SENIOR COMFORT Metrics and the ASHRAE Standards, the perception of variability dwindles over time, and the perception of variability is more prevalent at the 30-minute threshold for the SENIOR COMFORT Metrics and at the 15- and 30-minute for the ASHRAE Standards. These results indicate that residents may tend to perceive more changes in short periods of time and discomfort at those periods. At longer periods of time, residents seem to adapt and thermal variability is not significant. Table A4 summarizes whether the hypothesis is supported or not for this test.

Thermal Variability and Temperature Extremes

Thermal variability directly correlates with extreme temperatures, especially with low extremes. I conducted correlations between Minimum, Maximum and SD Temperature Composites with all thresholds outlined by the SENIOR COMFORT Metrics and the ASHRAE Standards. For all thresholds but one, minimum temperatures correlate with an almost absolute relationship. The only marginally significant correlation with a p-value of $p = 0.063$ was observed at the 15-minute threshold as outlined by ASHRAE. These results indicate that thermal variability prevails at low temperatures. Considering that older adults prefer higher temperatures, if temperatures drop below desired or preferred thresholds, we would expect that residents would manipulate their systems to increase temperatures which, in turn would increase thermal variability.

For Maximum Temperatures, correlations were also strong, although it was observed that only one correlation was significant for the SENIOR COMFORT Metrics at the three-hour threshold, while for the ASHARAE Standard thresholds, correlations at 15, 30, and 60 minutes were very significant. High correlations were expected for all tests and especially for tests between thermal variability thresholds and Standard Deviations, which also measure variability levels. Table A5 summarizes whether the hypothesis is supported or not for this test.

Building Attributes and Temperature Extremes

Building attributes, floor level, north and south orientation, and east and west wings were expected to correlate to temperature extremes. This expectation is stronger for the south and west orientations, which are most exposed to higher temperatures, during every afternoon in the Northern Hemisphere. See Table A5 for summary.

Floor and Temperature Extremes

Minimum temperatures did not yield significant results in relation to floor level. In fact, all relationships lacked statistical significance in this area. However, maximum temperatures were highly correlated to floor level, results showed a p-value of p=0.018. To identify the floor most affected by high temperatures, I conducted a Post-Hoc Tukey HSD, which indicated that the third floor was the most affected. Further descriptive information for Maximum Temperatures show that the mean temperature for the third floor is 83.91°F, much higher than that recorded, and then combined, for the first and second floors. For the first and second floors, mean temperatures for Maximum Temperature Composite were 81.72°F and 81.80°F. These results match expectations, as the third floor has an almost 1:1 ratio of exposed surfaces versus protected surfaces per apartment complex (almost as much surface walls are protected or neighboring other apartments as the walls are exposed to the roof and the elements). This condition makes the third floor perhaps more vulnerable to temperature changes and especially to high or low temperatures during the winter season. Winter conditions were not tested. See Table A5 for summary.

Orientation and Temperature Extremes

North and south orientations were expected to yield significant results. In the Northern Hemisphere, the sun rises in the east and the sun during the summer season reaches an azimuth of 81°F striking the buildings roofs specially and making all south-facing facades more susceptible to heat gain. For this reason, I expected that all south-facing apartments were going to be more affected by high temperatures than those facing north. My analysis of variance shows a strong, almost absolute, correlation between high temperatures and orientation with a *p*-value of p=0.004. In this case, a post-hoc test was impossible, because this test can only be performed between three items or more. Further analysis of descriptive information shows that mean calculations for max temperature composites by south and north orientation are not as expected. Mean for south orientation is 81.42°F and for north orientation is 83.36°F. These results are surprising, and the causes are unclear. I speculate that north apartment residents perhaps experience lower temperatures, which may lead them to mechanically increase their temperature or set their thermostat settings higher than those in south-facing apartments. Table A6 summarizes whether the hypothesis is supported or not for this test.

Wing and Temperature Extremes

I expected that east and west orientations would yield significant results; I expected that the west wing would record higher temperatures due to late-afternoon exposure to solar-heat gain. Once again, the results were unexpected, and no significance was recorded. The same trend was observed with temperature variations. Perhaps the amount of west-exposed wall on the west wing is too small in relation to the entire west wing and all units housed in that location, making this way any excess of temperatures on the west insignificant. See table A6 for summary.

Activity Behavior and Temperature Extremes

An activities composite was created and then, with resident HVAC manipulation, correlated to the maximum temperature composites, minimum temperature composites and temperature composites. None of these correlations yielded significant results. Previously, temperatures variations showed little correlation with activity levels and, on these tests, correlations do not show any correlations with activity levels of HVAC manipulations following the same trend. The no-significant correlation increases with max temperatures related to activity levels. The same can be observed for HVAC manipulation, which indicate that high temperatures may impact activity levels and HVAC manipulation. However, there is not enough information to elaborate on reasons why high temperatures are affecting either parameter. Table A7 summarizes whether the hypothesis is supported or not for this test.

Perceived Comfort and Extreme Temperatures

Perceived comfort was measured correlating Perception, Pain, Sleep Patterns, Injuries, and Mood with max and min temperatures as outlined by the SENIOR COMFORT Metrics and the ASHRAE Standards. Perception of comfort seems to be more prevalent and correlated with min temperatures, however the correlations were insignificant. As outlined by the ASHRAE Standards for minimum temperature thresholds, significant correlations were recorded for injuries and mood. For injuries, a high correlation was found *(p*=0.024) and for mood (*p*=0.040. This valuable information shows more injuries occur at lower temperatures and mood is affected, a finding consistent with the literature, which asserts that cold environments lead to more falls. (Tochihara, Tadakatsu, Nagai, Tokuda, & Kawashima, 1993). The ASHRAE Standards outlined a min temperature for summer conditions of 73°F, and SENIOR COMFORT metrics outlined a minimum of 76°F. All correlations for the SENIOR COMFORT Metrics were insignificant, a good indicator in this situation, assuming that when correlating higher temperatures, fewer falls or mood effects are recorded and, when testing against lower temperatures as outlined by the ASHRAE Standards, more issues are recorded. Table A8 summarizes whether the hypothesis is supported or not for this test.

Conclusions

Designing adequate guidelines for thermal comfort for populations at different ages and health conditions will enable residential designers, builders, mechanical engineers, and material developers, to create better housing units. These housing units will not only be more efficient, but will provide healthier indoor environment for older adults that can increase their quality of life and well-being. Aging adults experience loss of their physiological capacities to thermoregulate and, as physical activity decreases, metabolic levels decline. Although individuals differ, most will find their ability to interact with thermal changes affected, as well as their preferences for indoor temperatures.

The comfort zone as recorded at the Sunnyslope Manor was between 75.51°F and 82.39°F, with a total comfort zone window of 6.88°F. The ASHRAE Standard thresholds for min and max temperatures are 73°F and 81°F, with a total comfort zone window of 8°F. The SENIOR COMFORT Metrics min and max thresholds are 76°F and 83°F with a total comfort zone window of 7°F . While this may apply only to Sunnyslope Manor and conditions observed in this location, it seems that for recommended high and low indoor temperature thresholds for summer and for the Phoenix Metro area, the SENIOR COMFORT Metrics are slightly more accurate predictor for that particular parameter. Still, further research is needed, as 38% of all apartment units recorded temperatures above the recommended 83°F SENIOR COMFORT Metrics.

Older adults, as a group, might prefer even higher temperatures that those outlined by my designed SENIOR COMFORT Metrics. However, higher temperatures could yield unintended results, such as hyperthermia in controlled spaces where adults lack direct access to their thermostats or overuse of smaller mechanical systems in dwellings where systems based on higher temperatures were designed. Overuse could lead to more mechanical-system repairs, excessive cost, and higher temperature variability, as systems would run more frequently, and reduced indoor thermal comfort.

Thermal variability yields little significant results; most significant correlations were recorded related to building attributes; floor level and all orientations. However, it appears that it has little effect on human behavior—it did not affect the perception of comfort, pain responses, sleep patterns, increase or decrease injuries, or alter mood.

Thermal variability was slightly correlated to HVAC manipulation, but results are inconclusive. Again, result reflects building systems or building attributes. More research is needed to validate the new standards that limit or expand indoor thermal variability, especially for older adults. Behavior appears to significantly affect the level of HVAC manipulation and thus increases thermal variability. However, it was just one threshold displayed those results, eliminating the possibility of a stronger trend supporting this argument. There is no doubt that variability has a place in thermal-comfort recommendations for older adults. However, a larger human-subject sample and different unit types are needed to develop more conclusive recommendations.

As expected, temperature extremes strongly correlate to building attributes, all orientations, and floor levels. However, little evidence was found that high temperatures were substantially affecting the perception of comfort, pain or sleep patterns. As outlined by ASHRAE Standards, minimum recommended temperatures it was observed that injuries and mood were correlated with low temperatures when tested as outlined by the ASHRAE Standards. Both correlations were strong and the literature supports these results. (McGeehin & Mirabelli, 2001)

Recommendations

ASHRAE and ISO, as the leading research and standardization organizations, have considerable intellectual and financial resources to expand on this research and enact changes in their standards for older adults. I propose two recommendations:

1. Expand research and explore the adjustment of thresholds for high and low temperature design standards for older adult populations across all climate regions and include greater sample sizes.
2. Expand research on thermal variability and how this affects the thermal comfort of older adults and

These two changes will benefit older adults at different ages. Finally, while my research is inconclusive here, both organizations could make their indoor thermal design standards more stringent to make thermal environments more stable. Other considerations should include, for some regions, the design of new, flexible residential standards that allow for more human adaptability and interaction with the outdoor environment.

Lastly, thermal recommendations should be customized for different ages and stages in life, although further research is needed to support this recommendation. Our needs change as we age, and we should design for these changes. Currently, the rigid standards and suggested parameters that ASHRAE proposes for working places and working-age, healthy individuals do not accommodate the unhealthy, the old, the disabled, children as well as different behaviors and active and constant interaction between indoor and outdoor spaces.

Contributions to Health, Thermal Conditions, and Comfort for Older Adults

Thermal comfort standards focused their recommendations for working environments and healthy working-age individuals. Those standards are clear in pointing out that while most of their research is on these environments, they could be modified for residential use. However, it is unclear on how effective or accurate these methods might be. Furthermore, they do not outline older adults' different preferences, activity levels,

or behavioral conditions, which could all serve to inform modifications to their model. For example, these standards do not address sleep and rest activities, or thermal variability pertaining to older persons, and the ability of this population to thermoregulate during those temperature changes. (ASHRAE-55, 2010) (ISO 7730, 2005) (ISO-14415, 2005) On the other hand, environmental psychologists, health researchers, and other investigators have established that:

1. Older adults cannot thermoregulate as efficiently as younger adults' they are more susceptible to frequent indoor temperature changes over specific time periods.
2. Older adults' metabolic rate is also lower, therefore their basal core-body temperature is lower, in part due to the decreased physical activity.
   This condition exposes older adults to more discomfort with lower temperatures as established in mainstream standards such as ASHRAE 55 or ISO 7730. The need for specific standards addressing slightly higher temperatures and relatively stable temperatures avoiding temperatures swings for older adults is needed. (Basu & Samet, 2002; Gomolin, Aung, Wolf-Klein, & Auerbach, 2005; Havenith, 2001; Kenney & Munce, 2003)

Despite extensive health-related research and the highly developed thermal comfort standards, little effort has taken place to link these two sectors to develop specific standards for thermal conditions and thermal comfort for older adults.

This study explored the link between mainstream thermal comfort standards and perceived comfort and health conditions of older adults, adding information to this body of knowledge. One main goal was to diminish the fracture between those standards and existing older adults' research on temperature and indoor thermal conditions. To achieve this goal, this study tested the efficacy and acceptance of new proposed metrics to measure thermal comfort and thermal conditions for residential indoor environments for older adults and its effects on actual and perceived health. The new SENIOR COMFORT Metrics seem to be a better predictor for indoor thermal comfort for older adults.

Research Strengths

Perhaps the greatest strength of this research is that study along with the Green Apple Project is one of the first few nationwide studies to try to unravel how temperatures, including temperature variations affect the health and comfort of older adults. Many studies have been conducted suggesting that older adults are relatively more sensitive to temperature changes or that prefer higher temperatures due to physiological changes as we aged, specially diminished thermoregulation capacities (Havenith, 2001). Despite the fact that we possess this information, specific standards have not been developed suggesting or making systematic recommendations for the thermal design of residential units for older adults and/or individuals with disabilities that are hypersensitive to temperature changes.

The correlation of indoor thermal conditions with specific self-reported health conditions start indicating clear trends of thermal preferences or conditions that affect health and comfort. While these trends and indicators need to be furthered researched, they show a clear direction for future studies and also for the future characterization for standards on specific thermal recommendations for the design of homes housing older adults or individuals that need more-stable indoor thermal environments. Furthermore, this dissertation proposes a parallel system to the ASHRAE-55 Standards; the new SENIOR COMFORT 2013 Metrics outlined new thermal thresholds and allowances that could increase the comfort and health of older adults. Other very notable strength is the various correlations exclusively assessing thermal variability and its effects on health and comfort. The SENIOR COMFORT Metrics also proposed new allowances for variability, suggesting tighter standards for this portion of the study.

Research Limitations

The limitations of this study require consideration. The nature and particular characteristics of the sample may not represent the larger population, especially that of younger adults and adults with greater access to income, thus greater access to healthcare, personal care or personal assistance and technology which could ease their daily lives.

I collected indoor environmental data recorded over a five-day period, and outdoor environmental conditions changed over time, perhaps affecting perceptions due to changes that were not controllable. Research design and methods were partially based on the Green Apple Project design, however all correlations presented in this study, including composites, are original to this dissertation.

Finally, this study was conducted during the summer, when residents rely heavily upon air-conditioning and enjoy little-to-no outdoor natural ventilation. My selection limits the range of this study, which does not cover colder conditions and the effects of outdoor temperatures on behavior, perceptions, and comfort in and out of their apartments. Although outdoor thermal conditions were considered for this study, it was decided to not adjust for those conditions. Knowing that older adults spend the most of their time indoors, I considered only indoor thermal conditions for all correlations and statistical analysis.

Future Research, Overall Recommendations

Although the study's findings contribute to the literature and argue for new standards and more accurate design-standard recommendations for indoor thermal conditions for older adults, the link among other health factors (e.g., sleep patterns or physical activity) remain unanswered. We need to further explore the impacts of thermal comfort (and the perception of thermal comfort) on the health of older adults and their perceptions. For example, although the literature demonstrates that thermal variability affects sleep patterns or increases falls, the results based on actual conditions at Sunnyslope Manor were inconclusive.

As individuals age, activity levels decrease (Havenith, 2001), yet the extent of high or low temperatures, or thermal variability, on functional abilities or level of mobility is unclear. Aside from the obvious effects that building attributes have on indoor thermal conditions; it was inconclusive if these moderating factors were correlated at any level with the perception of comfort, pain, and sleeping patterns. To adjust for thermal adaptability and its effects in the perception of thermal comfort, future research needs to include outdoor thermal conditions. The same can be said for including detached housing units, where thermal variability can be more prevalent (because more walls are exposed to the elements, increasing solar heat gain or heat losses, which could also affect high and low indoor-thermal conditions over 24 hours).

The level of services and personal support to conduct daily activities found in public multi-housing complexes is much greater than that experienced by older adults living independently in their own homes. For example, residence maintenance, emergency services, access to personal assistance to get on and off a bus, assisted transportation to grocery stores, organize activities and others. The Sunnyslope Manor is not a full assisted living facility. However, many activities are organized by residence manager and social workers on site. This support might determine comfort, both perceived and actual, and overall quality of life.

Future research will need to study a larger human subject sample and a diverse housing stock to be able to extrapolate and generalize the SENIOR COMFORT Metrics recommendations to all residential environments. The expansion of the sample size will bring more credibility and further validate the study's findings. Finally, we need to build a more-elaborate survey with more specific questions addressing the perceptions of thermal comforts and actual thermal conditions. Specifically, we need to include a longer-temperature and relative-humidity testing trial as well as study indoor air velocity and thermal behavior. The expansion and more specific testing could yield valuable data on the effects of low-relative humidity on skin rashes, respiratory conditions, and allergies.

This study adds to the foundational literature in thermal comfort and its effects on older adult health and their perceptions of thermal health, it also calls for developing new and more specific standards for one of our most vulnerable populations. Elderly populations will increase by the millions as baby boomers retire. Not only will more-specific thermal design standards for older adults' indoor residential bring about a greater quality of life, but healthcare costs will be reduced for future generations. It is my hope that this dissertation will sparks interest for future and more comprehensive research on this area, which I believe will bring benefits to all.

Future Research, Specific Recommendations

Thermal comfort perceptions and actual effects on health have been complicated to assess. In order to better understand actual thermal preferences of older adults and how indoor thermal conditions affect their perceived, comfort and actual health future research should include some of the following tests and recommendations: locations, protocols, specific thermal comfort survey, possible sample size, and expanded and more complex statistical analysis test trial lengths.

Unit type: Housing unit types are extremely important in test results. Housing units at Sunnyslope Manor were relatively insulated from the elements considering that they are attached in one single building complex. Testing single family detached units that are completely exposed to the elements in all orientations with different floor levels will yield different and more diverse thermal conditions trends and results. Perhaps thermal variability will show greater variations and thermal extremes will also be more frequent given the strong correlations observed at SSM between thermal variability and temperature extremes.

Construction Materials: Construction materials respond significantly different to the weather retaining or releasing heat at various rates. These differences will affect how indoor thermal conditions' dynamics evolve. Tested should be conducted in at least two different home construction types, regular wood framed and block homes.

Temperature and Relative Humidity Data Collection: This data is fundamental to understand indoor thermal conditions. Data should be collected in all participating residences for a minimum of 12 months every 15 minutes. Data then should be organized per season and then compared to actual and reported health conditions and thermal comfort. Outdoor thermal data should be also collected at the same rate and intervals to assess thermal adaptability by residents and how this affects the thermal preferences per season in the Phoenix Metro Area.

Thermal Comfort and Health Survey: Perhaps this is the most complicated segment of future research. The new survey should be design specifically to address thermal comfort and perceived health as follows:

a) Thermal comfort questions should include a specific scale of comfort, perhaps the same one that ASHRAE has been using for the past decades, the thermal sensation scale, see table 2 for details. This thermal comfort survey will need to be administered four times per month or once a week to have enough perceived comfort data to correlate with actual indoor thermal conditions in relation to all weather conditions.

b) Health survey should be limited to very specific questions that assess 1. Physical activity, 2. Mood, 3. Falls, 4. Sleep and 5. Skin condition. This survey should be administered at the same time than the thermal sensation scale survey, four times per month or once per week. This survey should be small and easy to administer over the phone. Ideally participating resident will give access to all of his medical records to assess actual doctor's visits and reasons for those visits. Data collected for this segment of the health survey might be difficult to access considering the highly sensitive information that could be access on this subject. The design of this survey should include the expertise of a medical doctor to develop the criteria as to what illnesses could have been cause, exacerbated or trigger by thermal conditions.

Statistical Tests: Data collected at Sunnyslope Manor is comprised of 34,048 thermal data points that were collected over a five period of time in 76 apartment units. The descriptive analysis of these data show that 38% of all individuals maintained their apartment indoor temperatures above the maximum temperature recommended by the SENIOR COMFORT Metrics 2013 and 65% percent above the ASHRAE-55 2010 maximum temperature threshold. This information gives room to new questions regarding these residents that maintained their temperatures higher than 81 and 83 degrees Fahrenheit. Without collecting further data and instead using existing data, I would segment residents in three different groups.

a) Individuals with apartments that recorded temperatures below 81 degrees Fahrenheit.
b) Individuals with apartments that recorded temperatures above 81 and below 83 degrees Fahrenheit.
c) Individuals with apartments that recorded temperatures above 83 degrees Fahrenheit.

All three groups will be subjected to further statistical analysis that would include some of the following tests.

a) Pearson correlations between their specific reported health and indoor thermal conditions. Health indicators could be treated as independent variables for each correlation and progress into making new composites to determine more specific health and temperature correlations.

b) Correlations and regressions including covariates will play an important role for all tests. Different combinations could be tested to determine relationships and how different health conditions affect the perception of thermal comfort and vice-versa.

Future research as mentioned earlier will include outdoor thermal conditions. With that data I would conduct the following tests in addition to tests above this section.

a) Correlations, including covariates between indoor thermal conditions and furthermore between all health related indicators, physical activity, mood, falls, sleep and skin condition.

Sample Size: This number might be difficult to determine at this stage. However, in order to increase the possibility to start to generalize or make policy recommendations to regulate indoor thermal comfort for older adults a greater sample size needs to be calculated through a formal and well-designed sample power analysis. Current studies include sample sizes of between 40 and 80. However, none of them attempt to generalize their results.

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APPENDIX A

SUMMARY OF SIGNIFICANT FINDINGS

Summary of Significant Findings

The following tables outline significant findings and their relationship to the hypotheses.

Table A1
How Does Age and Gender Affect Thermal Variability?

Hypothesis

Older adults may maintain their thermal variability more poorly than younger adults.

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	For age	Not significant	No
SENIOR COMFORT Metrics 2013	For gender	Not significant	No
ASHRAE-55 2010 Standards	For age	Not significant	No
ASHRAE-55 2010 Standards	For gender	Not significant	No

Table A2
Do Building Attributes (Including Location and Orientation) Influence Indoor Thermal Variability?

Hypothesis

South- and west-oriented units will be more directly exposed to solar radiation; as a result, these units will experience more and greater temperature fluctuations, therefore increasing the frequency of health and thermal comfort related problems.

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	By floor	Not significant	No
ASHRAE-55 2010 Standards	By floor at 15 min	0.051	Yes
ASHRAE-55 2010 Standards	By floor at 30 min	0.048	Yes
SENIOR COMFORT Metrics 2013	By orientation at 30 min	0.031	Yes
	By orientation at 1 hour	0.039	Yes
ASHRAE-55 2010 Standards	By orientation at 1 hour	0.041	Yes
SENIOR COMFORT Metrics 2013	By wing at 3 hours	0.025	Yes

Table A3
Does Resident Behavior Influence Indoor Unit Temperature Variability?

Hypothesis

Residents who maintain varied levels of physical activity will manipulate HVAC controls or window operation in excess, resulting in more-frequent indoor temperature fluctuation.

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	By Activity level	Not significant	No
ASHRAE-55 2010 Standards	By Activity level	Not significant	No
SENIOR COMFORT Metrics 2013	By HVAC manipulation	0.012	Yes
ASHRAE-55 2010 Standards	By HVAC manipulation	Not significant	No

Table A4
How do Temperature Variations Affect Health and Perceived Comfort of Older Adults?

Hypothesis

More-stable indoor thermal conditions in relation to those outlined by ASHRAE-55 2010 in its temperature variability section will increase health and perceived comfort of older adults.

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	Perception of thermal comfort	0.076	Yes, Near-marginal
ASHRAE-55 2010 Standards	Perception of thermal comfort	Not significant	No

Table A5
Do Units with Frequent Temperature Variations Experience Extreme Temperature Values?

Hypothesis			
Frequent temperature variations correlate with extreme temperature values.			
Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	Variability & min temps at 30 mins	0.002	Yes
	Variability & min temps at 1 hour	0.000	Yes
	Variability & min temps at 3 hours	0.000	Yes
	Variability & max temps at 3 hours	0.000	Yes
ASHRAE-55 2010 Standards	Variability & min temps at 30 mins	0.049	Yes
	Variability & min temps at 1 hour	0.001	Yes
	Variability & min temps at 2 hours	0.000	Yes
	Variability & max temps at 4 hours	0.000	Yes

Table A6
Do Building Attributes (Including Location and Orientation) Influence Indoor Thermal Extremes?

Hypothesis			
South- and west-oriented units will be more directly exposed to solar radiation; as a result, these units will experience more and greater temperature extremes, therefore increasing the frequency of health and thermal comfort related problems.			
Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
Extreme max temperatures	By floor	0.018	Yes
Extreme max temperatures	By orientation	0.004	Yes
Extreme max temperatures	By wing	Not significant	Not

Table A7
Does Resident Behavior Influence Indoor Unit Temperature Extremes?

Hypothesis			
Residents who maintain varied levels of physical activity will manipulate HVAC controls or window operation excessively, resulting in more-frequent indoor temperature extremes.			

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
Extreme temperatures	Extreme temperatures, max and min	Not significant	No

Table A8
How Do Temperature Extremes Affect Health and Perceived Comfort of Older Adults?

Hypothesis			
More-stable indoor thermal conditions in relation to those outlined by ASHRAE-55 2010 in its temperature extremes section will increase the health and perceived comfort of older adults.			

Metric	Factor	Correlation, *p*-value	Do correlation results support hypothesis?
SENIOR COMFORT Metrics 2013	By min temperatures & all factors	Not significant	No
	By max temperatures & all factors	Not significant	No
ASHRAE-55 2010 Standards	By min temperatures & injuries	0.024	Yes
	By max temperatures & mood	0.040	Yes

APPENDIX B

TEMPERATURE SENSOR LOCATION AND TYPICAL FLOOR UNIT PLAN

B1. Temperature Sensor Location and Typical Floor Unit Plan