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Review Paper

A Review of the Foundations of Thermal Comfort Methodology in the Built Environment

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Abstract
Achievement of thermal comfort in the built environment is one of the human life needs. Many studies have already explored the issues around human comfort in relation to the surrounding thermal environment. However, most of these studies used quantitative methods that fall into the positivist paradigm. Despite the conducive results obtained, many aspects of the thermal comfort are neglected as the nature of comfort is directly associated with the human dimension. Therefore, it is necessary to adopt a different approach such as qualitative and mixed methods to better understand the underlying mechanisms of thermal comfort concept and its achievement. These methods could reveal other aspects of human comfort that have not been considered. However, the application of these methods requires fundamental knowledge of ontology and epistemology. Therefore, this paper reviewed and compared the dynamics of the application of the paradigms in thermal comfort studies and their methodologies. Analytical findings among the methods of studying thermal comfort showed that only quantitative studies were not sufficient to create the applied knowledge in this vein. As this is a human-based field, its methodology should be first selected and then designed in the right way respecting the context where a study is going to be carried out. In this process, qualitative studies can determine contributing factors, then quantitative studies can find the relationships between these factors.

Keywords: *Thermal comfort, Thermal pleasure, Environmental design, Energy saving, Methodology, Quantitative and qualitative research methods.*

1. INTRODUCTION

The growth of the world economy results in increasing energy demand (De Cian & Wing, 2019). Buildings account for a large portion of energy consumption which offers potential for energy savings and reducing CO_2 emissions (Kamal, Al-Ghamdi, & Koç, 2019). Most of the energy used in a building allocated to occupants' indoor thermal comfort (L. Yang, Yan, & Lam, 2014; Brunsgaard, Heiselberg, Knudstrup, & Larsen, 2012). Therefore, the study of thermal comfort in the built environments is one of the particular importance in sustainability and energy efficiency (Wu & Chen, 2017). Thermal comfort research is a branch of science that roots into an interdisciplinary approach and has evolved through the theoretical development of a human-place relationship.

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Comfort is defined as a sense of physical and psychological ease which is often known as lack of hardship. Since both physical and psychological aspects define the conditions of comfort, it has both internal and external dimensions. Table 1 summarizes different definitions of comfort.

Given all these definitions, thermal comfort could be described as satisfaction with environmental heat, so that people do not feel hot and cool. All these definitions emphasize the necessity of focusing on heat to provide a comfortable life for humans, and this subject, along with the importance of reducing energy consumption, give significance to thermal comfort study.

The importance of thermal comfort could be outlined as follows (Raw & Oseland, 1994; Taleghani, Tenpierik, Kurvers, & Van Den Dobbelsteen, 2013):

1- Providing desired conditions for people (providing desired thermal conditions, improving air quality and occupants' working efficiency)

2- Controlling energy consumption (economizing energy consumption, reducing environmental damages by decreasing CO_2 production)

3- Proposing and regulating effective standards

4- Reducing the cause of symptoms of sick building syndrome and enhancing people's well-being.

This point should be admitted that "comfort" includes mental conditions with a positive feeling and stress reduction. Therefore, its main research achievement is having benefits for people's physical and mental health through which serious actions have been taken to enhance the built environment quality.

Table 1. Definitions of Thermal Comfort (Source: Authors)

Source	Definition of comfort
Dictionary	"being relaxed and free from pain"
ASHRAE	"mental conditions" that implies the combination of physiological and psychological aspects
Benziger	a state in which people do nothing to change the thermal characteristics of the environment (Benzinger, 1979)
Limb	thermal pleasantness for occupants (Limb, 1992)
Olgyay	a state in which the least energy is consumed to create the desired environment (Olgyay, 2015)
Givoni	not complaining of heat and cold (Givoni, 1992)
Biology	maintaining hemostasis reaction to the environment, which demonstrates a lack of environmental stressors and is completely related to health (Ortiz, Kurvers, & Bluyssen, 2017)

Studying thermal comfort conditions which depends on human beings physiological and psychological dimensions and their surrounding environment has some ongoing theoretical as well as practical challenge (Schweiker, Schakib-Ekbatan, Fuchs, & Becker, 2020). The main root of its criticisms concerns defining "thermal comfort". Based on the definition provided by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), "thermal comfort is the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55, 2017; Spagnolo & de Dear, 2003). Since thermal satisfaction is subjective and essentially abstract and cannot be merely quantified, satisfaction with a given thermal environment depends on several factors, which are usually context-based (Schweiker et al., 2020). Therefore, studies on the interaction between a human and the context of his life cannot be conducted through any method. Although thermal comfort models attempt to explain some parts of thermal satisfaction (Nikolopoulou & Steemers, 2003), they are unable to fully describe how satisfaction is obtained from an environment. Most of the thermal comfort studies are not involved in the investigation of occupants' real life. As a result, buildings and their in-built cooling and heating systems are designed and constructed without a realistic view of users. In some of these studies, for example, researchers believe that they must decide what to offer to users as passive recipients of thermal conditions because the users do not have enough professional knowledge (Karjalainen & Koistinen, 2007). A closer look at the documented research on thermal comfort also shows that although significant progress has been made in many aspects of building physics and HVAC, its applicability to building occupants who judge satisfaction through their own condition is questionable. Some post-occupation evaluation studies show that although buildings are designed and built to thermal comfort standards, their occupants have different thermal behaviors in practice (Andersen, Fabi, Toftum, Corgnati, & Olesen, 2013; Fabi, Andersen, Corgnati, & Olesen, 2013). As the main responsibility of those studying thermal comfort is to solve occupants' comfort-related problems, the role of occupants should be considered.

Today, there is a growing trend in thermal comfort studies (Shooshtarian, 2019). Thermal comfort studies are generally costly (Haghighat, Allard, Megri, Blondeau, & Shimotakahara, 1999) and therefore the study methodology must be carefully designed in each situation By clarifying the methodological position, the researcher can design methods and techniques appropriate to the purpose of his research. One of the main reasons for this discrepancy between research results and field evaluation is the incorrect design of research methods. Because the researcher in identifying the main reason for the study of thermal comfort in the target context, mistakenly chooses a method which results are not efficient in practice.

Most researchers in the field of thermal comfort, because they look at this concept from an engineering point of view, ignore the human role and its deep dimensions. Hence, we are faced with a mass of quantitative research but far-fetched on human life. Assessment method selection depends on researchers' ontological, epistemological, and methodological assumptions. This article tries to explore thermal comfort research methods through an analytical review. Hence, from the lens of identifying methodological roots, explain the foundations (the ontology and epistemology) of each of these methods. This article can help future researchers to choose the appropriate method to study thermal comfort in their desired context to provide more practical achievements.

2. FOUNDATIONS OF KNOWLEDGE ELEMENTS

The overarching construction of the methodological approach is the paradigm, defined as a comprehensive value and belief system, which directs research and action in a science field (Strauss & Corbin, 1990). Kuhn claims that the paradigm of a science field lasts for a long time. However, gaps are found which challenge the existing paradigm and lead to scientific transformation. Therefore, a new paradigm emerges after a while, and a new scientific period begins. Meantime, the point should be focused that the answers to “what is the reality of a phenomenon? (Ontology)”, “what is the knowledge nature about the phenomenon? (Epistemology)” and “how the knowledge is achieved? (Methodology)” are not alike in different paradigms.

This section gives an outline about ontology, epistemology, and paradigms that embrace three categories of objectivism, subjectivism, and constructivism. Methodology and theorizing are then explained based on their foundations and entities.

2.1. Ontology, Epistemology: Review of Paradigms

Research methodology is one of the major challenges for thermal comfort researchers (de Dear, Xiong, Kim, & Cao, 2020; Luo, Wang, Brager, Cao, & Zhu, 2018). However, responses to the challenges is rooted in ontology and epistemology of study subjects that are not separate from each other and clarify study foundations, on which researchers often do not have enough information.

Ontology constitutes the main core of the study, observing the studied reality. Ontology examines the concepts which directly concerns creating and existing a phenomenon and its related affairs. Research ontology reflects “researcher’s attitude to world nature” (David Marsh, 2002), his/her position in answering “what is the reality of the phenomenon?” (Krauss, 2005).

Epistemology of the study subject is clarified based on ontology, dealing with nature and justifiability of science. In fact, epistemology seeks to discover an appropriate science for understanding the subject based on the accepted ontology. Therefore, epistemology could answer “what is the relationship between subject and object?”, “what does justify understanding the object?”, "What is its structure, and what are its limits?" and "Is justification internal or external to one's own mind?" (Krauss, 2005; Norman Denzin, 2008).

A science field should create a frame of thought alongside a set of models, theories, and hypotheses if it aims to communicate with its justified ontological and epistemological roots. The paradigm is a comprehensive system of thought which directs research and action in the study scope (Strauss & Corbin, 1990) and implements epistemological foundations in research implementation.

In general, studies could be divided into three epistemological approaches including objectivism, subjectivism, and constructivism which are rooted in their own ontology and ollowed by different paradigms.

2.2. Objectivism

Objectivism is rooted in the modern philosophy developed by Descartes regarding the mind and separable body (Hart, 1996). “Objectivism” is an epistemological approach that considers the existence of things (being, entity) to be meaningful in an object. Objectivism views humans role as a connector, who directly communicate with and understand reality by their sense. In addition, this approach supports the positivist paradigm in which phenomena related to humans such as the physical world (independent of human mind) could be discovered by scientific tools and evaluated separately (Crotty, 1998). Researchers can investigate the phenomenon independently and without affecting the subject or being affected by it (Sale & Lofeld, 2002).

2.3. Subjectivism

Despite objectivism, subjectivism considers knowledge and all rules and standards to be subjective (Alan Richardson, 1989). In the approach, knowledge ultimately refers to personal objective perceptions that illustrate the entity of each object. The ontological foundation of the approach gives originality to human mind in knowing reality. However, it has no definition for human role in changing this reality. In fact, human knowledge in the subjectivism approach is the result of the context, in which he/she has grown up. However, the human cannot affect or change that context.

2.4. Constructivism

Since the mentioned two approaches are not separable, a phenomenon being known objectively and subjectively needs to be brought and held together named constructivism. In this approach, meaning is not discovered but constructed; subject and object emerge as partners in the generation of meaning. What constructivism claim is that meanings are signified and interpreted as engagement with the world by a human. In fact, as an influencing and influenced factor, human role is more significant than that of subjectivism and objectivism. Additionally, the context of engagement (human’s behavior and experiences) between humans and phenomena is important. Therefore, phenomena could not be totally perceived if they are separated from their context. The paradigms include phenomenology, interpretationism, and naturalism, which follow the ontology of this approach and emphasize human environmental perception (Crotty, 1998). Table 2 summarizes these three approaches.

The present study aims to clarify obscure points and commonly-used terms and methods in studying thermal comfort by comparing philosophical and methodological foundations. Therefore, the study deals with the epistemological, ontological, and methodological introduction of common qualitative and quantitative methods. Then, through gap analysis of related studies, it assesses the situations and dimensions of current studies by the systematic review approach.

Table 2. Summary of Three Epistemological Approaches (Source: Authors)

Methodology	Application in thermal comfort research	Reality	Entities
Objectivism	- Quantitative studies - Temporary thermal comfort studies	Objective, visible and measurable affairs perceived by senses (Lehrer, 1974)	Researcher and study subject
Subjectivism	-Describing everybody's subjectivity, different from others.	Human's image of world phenomena (Crotty, 1998)	Personal perceptions Away from interactive effects
Constructivism	- Describing how human perceives in living context and in interaction with the environment (Crotty, 1998).	Depends on human's actions constructed by their engagement with their world	Human, phenomenon, the context of engagement, and interaction between them

2.5. Theoretical Foundations

The methodology determines how concepts are to be known and as methodology changes by changing the paradigm, it originates from the paradigm (LeBlanc, 1995). The methodology is defined as a systematical and theoretical analysis of strategies used in both a study field and a special subject (S.I. Irny, 2005). Blaikie claims that the methodology provides general strategies for forming, articulating, analyzing, and assessing the study and requires ontological and epistemological assumptions (Norman Blaikie, 2009). In addition, the methodology is defined as "theory and analysis on the way of study implement" (Harding, 1987) and "investigating description, definition, and justification of methods (not investigating methods)" (Carter & Little, 2007). In terms of a researcher's epistemological positions, three methodological approaches could be introduced: qualitative, quantitative, and mixed methods. At this stage, researchers find and use a special method by which data is collected and analyzed, or certain techniques are utilized based on a special hypothesis.

Knowing the reality is considered as the final aim of all scientific studies which needs an appropriate methodology rooted in philosophical foundations. The foundations form a powerful mediator to link philosophy to science that is played by the paradigm, relying on the foundations. Inkeles defines theory as follows: "theory is regarded as a tool for organizing something we know or imagine to know about an almost explicit problem in a given time" (Inkeles, 1964). Turner sees theory as a "story" about how and why events happen in the world (Turner & Turner, 1978). Land considers theory as a set of notions and phrases expressing the relationships between concepts (Land, 1971). Theories finally provide some models for stating the knowledge acquired from the reality. A study strategy is also determined based on selecting the study paradigm (Norman Blaikie, 2009). The strategy which is defined as the logic ruling on the study demonstrates the way of study argument. In quantitative methods, the researcher discovers the reality by deductive reasoning; while in qualitative methods, the researcher uses inductive reasoning on the existing reality to reach a theory about knowing that reality. Figure 1 illustrates the process of foundations of a scientific study.

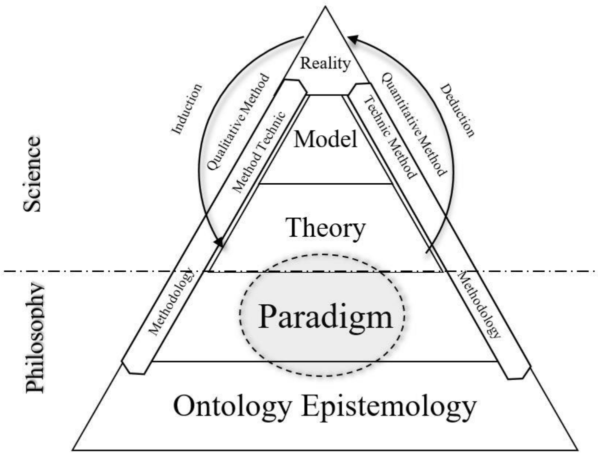

Fig 1. The Process of Foundations of a Scientific Study (Source: Authors)

3. METHODOLOGY

This study used the content analysis technique to collect secondary data publicly available. Data collection was carried out in the following steps:

1. Initially, for all studies on 'Thermal Comfort', a desktop search was performed through six major databases: Google Scholar, Scopus, PubMed, Wiley Online Library, ProQuest, and Web of Science.
2. This research was done with the keywords "Thermal Comfort", "Energy Saving" and "Building", leading to a variety of sources, including journal articles, doctoral dissertations, and related conference papers.
3. In the next stage, the environment-related resources were created in a separate list, and their full text was carefully reviewed. In particular, sources that did not consider the use of a "theoretical framework" or "thermal comfort in a space other than the built environment" were excluded from the study.
4. The sources were then categorized based on the topic and their relationship to 'thermal comfort' as the main phenomenon, and the full text of the selected sources was subsequently coded and archived for the final stage of review.

Finally, the selected sources were reviewed with three criteria: 1) the relationship between the subject of the article and thermal comfort, 2) study methods and techniques used, and 3) the dominant view of the researcher on designing research.

These criteria put different sources into more specific categories including qualitative, quantitative, and mixed methods. Finally, according to the purpose of the research, the methodology of thermal comfort studies, different categories of studies were analyzed in quantitative, qualitative, and mixed methodological groups.

4. FACTORS INFLUENCING THERMAL COMFORT ACHIEVEMENT

A review of various thermal comfort papers shows that this phenomenon has so far been considered in 6 general aspects (time, climate, structure, physiological, psychological, and human behavioral issues) (Figure 2). Each of these studies focuses on different variables. Some of these studies are reviewed below.

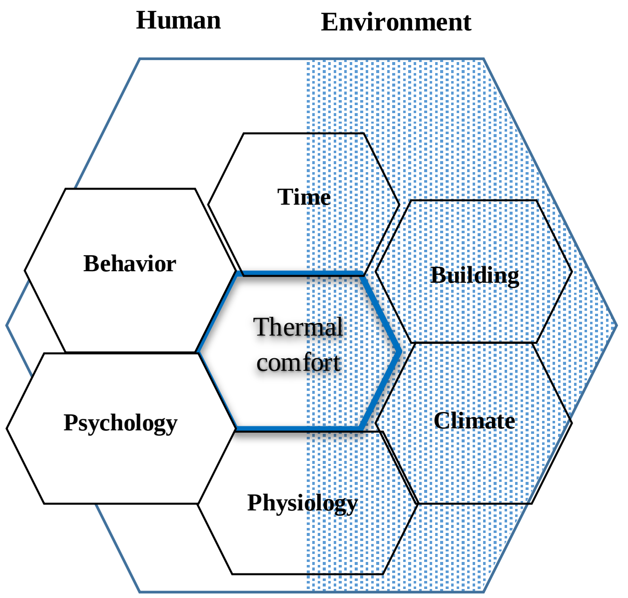

Fig 2. Main Factors Studied in Thermal Comfort Research (Source: Authors)

4.1. Time

Time unit (months, days, and hours) is regarded as an essential factor for how occupants reside in a building. Some personal behaviors are time-dependent, for instance, time of rest or opening and closing windows and turning heating devices off/down prior to leaving an office (Jing, Lei, Wang, Song, & Yan, 2019; Liu, Cen, Zhang, Liu, & Dang, 2016; Rodriguez & D'Alessandro, 2019).

4.2. Physical Factors

Climate: In most of thermal comfort studies, the discussion of climate is divided into macroclimate and microclimate. Macroclimate is the same extensive environment and consists of six main elements including temperature, atmospheric pressure, wind, humidity, rainfall, and cloud cover (Kumar & Singh, 2019; Muhsin, Yusoff, Mohamed, & Sapian, 2017). Their combination in each moment describes the weather conditions (Battan, Battan, Battan, & Battan, 1979). Microclimate deals with small areas of several square meters (for instance a central courtyard, garden, or greenhouse) or several square kilometers (Kumar & Singh, 2019; Muhsin et al., 2017).

Local data: In terms of the enclosure, a human's living area can be divided into outdoor, semi-outdoor, and indoor. Furthermore, studies explore variables such as vegetation (in forms of parks, street trees, green roofs, and walls) and reflective materials (on the roof and on the ground) (Latha, Darshana, & Venugopal, 2015; Rupp, Vásquez, & Lamberts, 2015; Isaksson & Karlsson, 2006).

The building is an enclosed environment which, after climate, provides human's thermal comfort. Studies on thermal comfort can have applied results in the building sections including optimizing thermal comfort levels in both new and old buildings. Reading a large number of studies on thermal comfort demonstrates that building studies, from many aspects, can play an important role in the formation of thermal comfort, in particular location (neighborhood and orientation) (Martinelli & Matzarakis, 2017; Kumar & Singh, 2019; Muhsin et al., 2017; Hussain & Oosthuizen, 2013), form (proportion, dimension, geometry (Martinelli & Matzarakis, 2017), form of envelope (May Tzuc et al., 2019), number of stories (Kumar & Singh, 2019; Muhsin et al., 2017; Hussain & Oosthuizen, 2013), envelope (material and technique) (Latha et al., 2015), operation schedule (intelligent/ manual) (Jung & Jazizadeh, 2019; Sung & Hsiao, 2020) function, (Rupp et al., 2015), and system (Opening/ window (Buratti, Moretti, Belloni, & Cotana, 2013; M. Liu, Wittchen, & Heiselberg, 2015), shading (Colter, Middel, & Martin, 2019), equipment (Kong et al., 2019; Muñoz-González, León-Rodríguez, & Navarro-Casas, 2016), thermost (Aghniaey & Lawrence, 2018), natural ventilation (Van Craenendonck, Lauriks, Vuye, & Kampen, 2018).

4.3. Human Factors

The knowledge of human-related subjects is a vital factor in the thermal design of buildings. Understanding human behavior under different conditions and environments is difficult. Humans continuously respond to living environment conditions and modify or regulate it. Such continuous modifications enable humans to achieve optimum and desired results and even survive under difficult climatic conditions. Relationship between human and thermal comfort can be discussed in terms of psychology (acclimatization/background) (Rupp, Kim, de Dear, & Ghisi, 2018; Chun, Kwok, Mitamura, Miwa, & Tamura, 2008; Yamtraipat, Khedari, & Hirunlabh, 2005) and Experience/expectation (Luo, Wang, Brager, et al., 2018; Rupp et al., 2018), physiology, age (Yun et al., 2014; Hughes, Natarajan, Liu, Chung, & Herrera, 2019; Giamalaki & Kolokotsa, 2019; Wang et al., 2018), race (Ogbonna & Harris, 2008), gender (Lu, Xia, Wei, Fang, & Qi, 2016), (Wang et al., 2018; Karjalainen, 2007), nutrition and health (Critchley, Gilbertson, Grimsley, & Green, 2007; Khodakarami & Nasrollahi, 2012), metabolic rate (Zhang, Zhou, Zheng, Oladokun, & Fang, 2019; Djamila, 2017; Luo, Wang, Ke, et al., 2018; Luo, Zhou, Zhu, & Sundell, 2016), and behavior (changing state, cloth volume and system settings) (Salata, Golasi, Ciancio, & Rosso, 2018; Oliveira, Gaspar, & Quintela, 2011; Djamila, 2017), which include many studies shown in Table 3.

Table 3. Contributing Factors in Achieving Thermal Comfort (Source: Authors)

Contributing factors to thermal comfort			References
Time	Hour, day, month, season		(Jing et al., 2019; Liu et al., 2016; Rodriguez & D'Alessandro, 2019)
Physical environment	climate	microclimate	(Kumar & Singh, 2019; Muhsin et al., 2017)
		macroclimate	(Haase & Amato, 2009; Albatayneh, Alterman, Page, & Moghtaderi, 2018)
	Local data	outdoor	(Latha et al., 2015; Rupp et al., 2015; Isaksson & Karlsson, 2006)
		semi-outdoor	
		indoor	
Building data	location	neighborhood	(Martinelli & Matzarakis, 2017)
		Orientation	(Haase & Amato, 2009; Albatayneh et al., 2018)
	Form	proportion, dimension, geometry	(Martinelli & Matzarakis, 2017)
		Form of the envelope (wall, roof)	(May Tzuc et al., 2019)
		number of stories	(Kumar & Singh, 2019; Muhsin et al., 2017; Hussain & Oosthuizen, 2013)
	Physical Envelope	material	(Latha et al., 2015)
		Design and building technic	(Hosseini, Mohammadi, Rosemann, Schröder, & Lichtenberg, 2019)
	Operation schedule	intelligent/ manual	(Jung & Jazizadeh, 2019; Sung & Hsiao, 2020)
	function	Type of occupants	(Rupp et al., 2015)
	Building feature	Passive/active	(Muñoz-González et al., 2016; Sayigh, 2013)
	System	Opening/ window	(Buratti et al., 2013; M. Liu et al., 2015)
		shading	(Colter et al., 2019; Sghiouri, Mezrhab, Karkri, & Naji, 2018)
		Equipment	(Kong et al., 2019; Muñoz-González et al., 2016)
		Thermostat	(Aghniaey & Lawrence, 2018)
		Natural Ventilation	(Van Craenendonck et al., 2018)
Human factors	Psychological	Acclimatization/Background	(Rupp et al., 2018; Chun et al., 2008; Yamtraipat et al., 2005)
		Experience/ expectation	(Luo, Wang, Brager, et al., 2018; Rupp et al., 2018)
	Physiological	gender	(Lu et al., 2016; Karjalainen, 2007; Schaudienst & Vogdt, 2017)
		Age	(Yun et al., 2014; Hughes et al., 2019; Giamalaki & Kolokotsa, 2019; Wang et al., 2018)
		Race	(Ogbonna & Harris, 2008)
		Health/food	(Critchley et al., 2007; Khodakarami & Nasrollahi, 2012)
		metabolic rate	(Y. Zhang et al., 2019; Djamila, 2017; Luo, Wang, Ke, et al., 2018; Luo et al., 2016)
		Sleep/Bathing	(Song, Liu, & Liu, 2018)
	Behavioral	Changing own state/ Changing system setting	(Jung & Jazizadeh, 2019)
		Changing clothing level	(Salata et al., 2018; Oliveira et al., 2011; Djamila, 2017)

5. RESULTS

5.1. Quantitative Method in Thermal Comfort Study

A quantitative study has a component-oriented approach to objectively describe variables and explain their relationships and reaches data often obtained by numerical measurements. The data are collected in a laboratory and controlled environment by techniques such as questionnaires, experiments, calculation, simulation, and well-organized techniques. In addition, methods of data analysis shape statistical analysis. In the quantitative method, knowledge and explanation of the subject are inappropriate without measurement and so as long as concepts of a theory are not experimentally measured, they are useless (Neuman, 2007). In many studies, given the scope, a combination of techniques is used. The main issue is to concentrate on the increasing role which computers and smart tools play in thermal comfort experiments and studies. Accessibility of data-collecting and thermal-simulating tools has a great influence on accelerating quantitative studies of thermal comfort. The most commonly-used objective techniques in thermal comfort research are outlined below.

Field Monitoring

Field monitoring is widely used to present a better understanding of environmental conditions as well as occupants' behavior regarding comfort conditions in buildings (Hong, D'Oca, Turner, & Taylor-Lange, 2015). Almost in all of the published experimental studies, occupants' behavior was observed in a particular location for a defined period. Therefore, a wide range of climate data should be used by field sensors (anemometers, thermometers, globe thermosets, hygrometers, etc.) to measure indoor and outdoor data of humidity, temperature, air speed, radiative temperature, and wind speed.

Laboratory Studies

Lab studies of thermal comfort aim to create a controlled and changeable environment according to the design of the experiment. These studies sometimes need almost-advanced equipment and tools in many universities and research institutes. These experiments include chambers and wind tunnels (Blocken, Stathopoulos, & van Beeck, 2016; Sadeghi, de Dear, Samali, & Wood, 2017) which provide a small-scale model to simulate what happens at a real scale and condition. Chambers are small laboratories that measure the effect of changing variables on human's thermal comfort (Taleghani et al., 2013; Rupp et al., 2015; Zhang, Zhang, & Khan, 2019; Soebarto, Zhang, & Schiavon, 2019). Thermal comfort studies in climatic chambers are based on neutral thermal sensation (Shahzad, Brennan, & Theodossopoulos, 2013) which is always recorded via questionnaires. Although environmental data in chamber space is often recorded by smart sensors, other effective tools such as infrared thermography make this measurement more accurate. This tool is considered a non-touch method and has no danger in measuring temperature (Sales, Pereira, Aguilar, & Cardoso, 2017). Although using chambers aims to control temperature more and reduce intervening parameters (Van Craenendonck et al., 2018), these experiments are designed with a definite hypothesis and the researcher is not free to modify them such as Wang et al. who compared the conclusion of a field study and a climatic chamber study (Wang et al., 2018). The wind tunnel is large tubes in which air blows in a specific direction and speed. The wind tunnel provides an environment simulating the effect of airflow. This small lab is also used to examine the effect of airflow on thermal comfort (Sadeghi et al., 2017).

Mannequins

Thermal mannequins are robots that are connected to smart sensors and measures any kind of heat transfer in total body area and in all directions. Thermal mannequins measure the effect of environmental conditions such as radiative asymmetry, spatial, and temporal variations of local airflow around the mannequin body, environmental temperature and its changes as well as heat transfer via surface contact (for instance, with chair, furniture, floor or other things) (Psikuta et al., 2017; Kong et al., 2019) on human physiological receptions. Moreover, cloth and personal protective equipment play an important role in environmental heat transfer which mannequins can measure directly (Oliveira et al., 2011). Some mannequins are even equipped with a smart transpiration system and can illustrate the effect of evaporative cooling (Psikuta et al., 2016). To this aim, there must be smart equipment recording the changes since assessing these effects via the human's body and skin is often not possible due to being animate.

Calculation

Estimation of thermal comfort quantity, especially in PPD and PMV models, is based on the Fanger method in which different models develop the calculation formulas of comfort rate and passive temperature given by environmental conditions and study objective. After selecting an appropriate model, the existing formula is used to calculate thermal comfort quantity (Shahzad, Calautit, Calautit, Hughes, & Aquino, 2018; ISO, 2005; Enescu, 2017). Today, there are also online software programs that calculate thermal comfort quantity by receiving existing data, such as CBE thermal comfort tool computing PPD, PMV, and SET quantity according to ASHRAE Standard 55-2017 and is available at https://comfort.cbe.berkeley.edu/.

Simulation

Today, a wide range of building energy simulation software packages have been developed, improved, and used during building energy studies. The advances in computer technology have led to an improvement in the ability to assess and optimize complicated physical and physiological conditions. Simulation not only greatly contributes to simplifying non-linear equations but also plays an essential role in the design or optimization of complex buildings to predict the occupants' comfort (Alahmer, Mayyas, Mayyas, Omar, & Shan, 2011; Enescu, 2017). It is also used in combination with other techniques. Therefore, computer simulation is considered a description to show thermal conditions which will occur in a real building. Today, researchers use simulation software programs to evaluate: 1) building energy efficiency, 2) thermal comfort levels, and 3) indoor air quality (IAQ). The most widely-used software include Energy Plus (Salehi et al., 2019; Muñoz-González et al., 2016; Buratti et al., 2013), Design Builder (Muñoz-González et al., 2016), ECOTECT (Anand, Deb, & Alur, 2017), TRNSYS (Buratti et al., 2013), DeST and ENVI-met (Barakat, Ayad, & El-Sayed, 2017; Karakounos, Dimoudi, & Zoras, 2018; Limona, Al-hagla, & El-sayad, 2019) as well as other developed programs. Some studies may use single software or a combination of some since each program has a different ability. Most of these programs calculate thermal comfort quantity by changing some variables (Anand et al., 2017; Pastore, Corrao, & Heiselberg, 2017). All these simulation programs have their own pros and cons. So, the decision to single each one out depends on their features and study scopes.

Questionnaire

A questionnaire is used when occupants' opinions on thermal sensation and their thermal preferences are highly important. These data are almost received by self-reporting (Lipczynska, Schiavon, & Graham, 2018) or various interview techniques and questionnaires [89] [189] (Ji, Cao, Luo, & Zhu, 2017; Yang, Olofsson, Wang, & Lu, 2018; Giamalaki & Kolokotsa, 2019; Luo et al., 2016; Fukuta, Matsui, Ito, & Nishi, 2015; Luo, Cao, Damiens, Lin, & Zhu, 2015; Karjalainen, 2007; Karjalainen, 2012; Tweed, Dixon, Hinton, & Bickerstaff, 2014; Critchley et al., 2007; Humphreys, Rijal, & Nicol, 2013). Further, examination of occupants' behavior is highly crucial because of time management, location recognition, change of clothes, activity, location, and conditions such as opening and closing windows or adjusting the thermostat. The surveys are usually performed on a large number of building occupants. These questions are generally accompanied by field, climatological information, and statistics (if applicable) to have an analytical value. Some sample questionnaires can be often found at the end of standards such as ASHRAE, which the researcher can modify them according to study objectives (ASHRAE Standard 55, 2017). However, preparing a questionnaire and asking some groups of people questions encounter some difficulties. For instance, it is definitely not easy to ask a child questions about their thermal sensation while having no correct perception of cold or heat. In this regard, the researcher has to use another technique to know about child feelings (Fabbri, 2015; Fabbri, 2013).

5.2. Qualitative Method in Thermal Comfort Study

The qualitative methodology is theoretically and methodologically different from quantitative method. Ontology and epistemology of the qualitative method are based on constructivism in which realities are made by human's cooperative perceptions (Williams, 1998; Babbie, 2013) but non-numeric data (IEA, 2017) which discuss meanings, definitions, perceptions, features, metaphor, symbols, and descriptions of phenomena, and not their size or number (L. Yang et al., 2014). There are no direct hypotheses in a qualitative study based on which the researcher can start the research, but with a question on a phenomenon (Leedy & Ormrod, 2005). Thereby, the qualitative study can discover an effective model fitted in a natural environment, and enhance details' level of real experiences (W Creswell, 2016). There are various methods for qualitative methods including case study, ethnography, phenomenology, grounded theory, content analysis, etc. By inductive reasoning of existing reality, these methods lead to a theory on the phenomenon under study while the researcher is outside the phenomena (Strauss & Corbin, 1990). Data can be collected by different techniques in a qualitative study including interviews, observation, and participation and can also be organized by software such as MAXQDA 2 (van Hoof & Kort, 2008) or NVivo (Healey & Webster-Mannison, 2012). However, qualitative interviews might be difficult and time-consuming because of interpreting a conversation, pursuing participant's answers, and modifying these answers proportionally to different positions (Isaksson & Karlsson, 2006).

From the beginning, evidently, most of thermal comfort studies have been conducted quantitatively, whose roots are in their knowledge foundations. However, by the time, different researchers have questioned the mere use of the methods (Shahzad et al., 2013; Michael, Humphreys, & Hancock, 2007). This subject forms the studies in which researchers seek to find how people really feel comfortable in a thermal environment. How humans perceive and behave cannot be discovered by quantitative methods measuring the relationships between variables. Thus, qualitative methods should be used to understand the issue in depth. Nicole et al. explained that due to the unique complexities of thermal comfort, further studies should be conducted to reach a better understanding in order to clarify and generalize conclusions (Nicol, Humphreys, & Roaf, 2012).

For promoting an occupant-oriented approach focusing on occupants' context and daily life, qualitative interviews are more successful (Isaksson & Karlsson, 2006) where a context is proportional to the study objective (Healey & Webster-Mannison, 2012), and then somebody is experiencing limitations and conditions in that context (Hitchings, 2009). In addition, the researcher must consider precisely people's behavior and lifestyle in the documentation process to claim credit for their study (Brunsgaard et al., 2012).

The principles of organizing and designing questions to achieve logical responses are also regarded as one of the researcher's challenges in qualitative studies (van Hoof, Kort, Hensen, Duijnstee, & Rutten, 2010); however, interestingly just a few thermal comfort studies have been applied other techniques than interviews such as the phenomenological method. For instance, Van Hoff and Kort tried to discover phenomenologically how people view technology's role in their routine (van Hoof & Kort, 2008), Shahzad et al. investigated "neutral thermal sensation" by grounded theory (Shahzad et al., 2013) or Strenger aimed to determine which factors promote occupants to readapt their thermal expectations or intend to adapt with different thermal conditions (Strengers, 2008). These issues are widely discussed by open questions (Karjalainen & Koistinen, 2007). During an interview, the researcher can even ask participants to show how to control the temperature of their location (Karjalainen & Koistinen, 2007) or provide some propositions (Isaksson & Karlsson, 2006).

In thermal comfort studies, adopting a qualitative method plays an important role in the detection and realization of hidden issues affecting occupants' comfort and satisfaction (Healey & Webster-Mannison, 2012). Therefore, this method can discover the role of factors rooted in human culture and context (Wilhite, Nakagami, Masuda, Yamaga, & Haneda, 1996). The interviews mainly aims to investigate ways of using controllers and, more broadly, occupants' behavior when they feel hot or cold, as well as to discover problems that occupants have with controllers (Karjalainen & Koistinen, 2007). For example, knowledge on HVAC systems in offices is less than in homes or gender differences in thermal comfort and use of thermostats might partly be due to differences in knowledge on HVAC systems. This idea is supported by this reality that women feel they have less control over room temperature than men (Karjalainen, 2007).

Brunsgaard et al. view the perception of thermal conditions at the heart of occupants' life as a requirement for the design and planning of passive and active systems. Thus, using qualitative methods provides a possibility by which the design of buildings and their systems come to the reality of occupants' behavioral specifications and lifestyle (Brunsgaard et al., 2012).

Thermal comfort contextual studies have been criticized due to their complexities and the variety of factors affecting thermal conditions. Nicol et al. claimed that conclusions of a grounded study may not be generalized to others due to context changes (Nicol et al., 2012).

It seems that considering the outputs of thermal comfort studies should be efficient for human life, the change and diversity of lifestyles in different parts of the world; so it is better to know the context and behavior of users well before testing thermal comfort variables. Based on this, the behavioral realities of users' lives would be extracted and then, it is possible to design a correct experiment and test the variables.

5.3. Mixed Methods

Quantitative and qualitative methodologists are often criticized due to the lack of attention to the context of phenomena and repeatability and generalizability of conclusions respectively (Sells & Smith, n.d.). However, many studies should complete the study process through the test of theory concluded by a qualitative study in order to make the conclusion applicable. Thus, a combination of both qualitative and quantitative methods could be used to obtain a deep and comprehensive perception of thermal comfort issues, called mixed methods.

In mixed methods, the researcher must select appropriate qualitative and quantitative techniques so that the mixture can make study questions compatible together. At first, some researchers threw doubts on this method discussing the incompatibility of fundamental philosophical views to combine qualitative and quantitative methods (Reichardt & Rallis, 1994). However, using this method after one decade, its practical foundations left no doubt (Teddlie & Tashakkori, 2003). Today, the results of studies conducted by mixed methods demonstrate an optimistic perspective for the knowledge of social and behavioral phenomena, and these methods are emphasized more than ever (W Creswell, 2016).

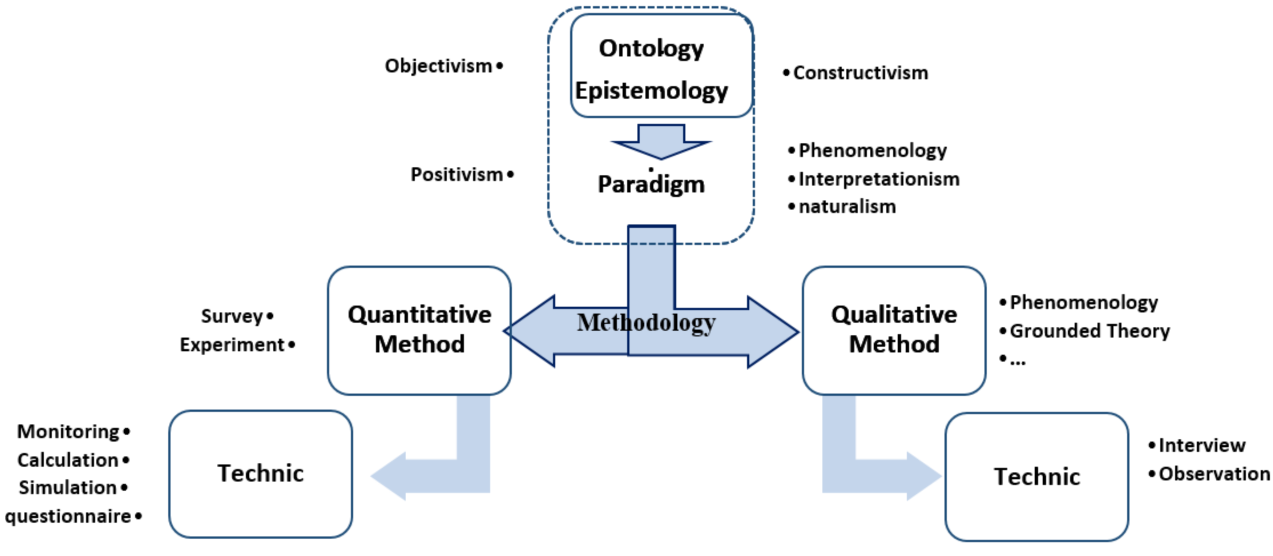

Fig 4. Analysis of Thermal Comfort Methodologies (Source: Authors)

Clearly, the main features of study methods are affected by how to use qualitative and quantitative methods which depend on the following features: a) amount of preference or importance devoted to two methods, and b) subsequence of using two methods (Creswell, 1999).

The researcher should justify the necessity of using both qualitative and quantitative methods when he/she is preparing a project study by mixed methods. To this aim, the researcher explains which method (quantitative or qualitative) is of the greater importance to be implemented in a study project. For instance, if a study aims to explain a phenomenon, it must first collect quantitative data, then clarify different dimensions of the phenomenon by gathering qualitative data.

Researchers collect and analyze not only quantitative data but also descriptive data with which dealing is regarded as a norm for qualitative studies in order to answer questions defined for the study. For instance, in order to collect a mixture of data, the researcher can distribute questionnaires carrying closed questions to collect quantitative data and also conduct interviews with open questions to collect narrative or qualitative data (Teddlie & Tashakkori, 2003).

Researchers use mixed methods to present strengths and minimize weaknesses of the study approach (Johnson & Onwuegbuzie, 2004), however, they are not absolute considering the context and researchers' attitudes.

In this method, researchers with a special scope design a combination of collected data or data analysis techniques from quantitative and qualitative research, are able to construct and test theories (Johnson & Onwuegbuzie, 2004). Of course, qualitative and quantitative research can complement each other through discovery (by qualitative research) and validation (by quantitative research (Isaksson & Karlsson, 2006; Brunsgaard et al., 2012; Brunsgaard et al., 2012). Currently, few researchers have used a combination of quantitative and qualitative methods to fully understand their target phenomenon for thermal comfort research (Table 4), but this does not diminish the importance of mixed methods. Brunsgaard and Heiselberg argue that using both quantitative measurements and qualitative interviews on indoor thermal comfort experiences of occupants leads to a more complete and comprehensive view of reality (Brunsgaard et al., 2012). Also, the experiences gained from using mixed methods show that these methods make it possible to better understand social and behavioral phenomena and explain them (García-Álvarez & López-Sintas, 2002; Teddlie & Tashakkori, 2003).

Table 4. Thermal Comfort Studies Based on Quantitative, Qualitative, and Mixed Methods (Source: Authors)

Source	Method			Achievement
	Mixed	Qualitative	Quantitative	
(Healey & Webster-Mannison, 2012)	✓	Semi-structured interview	Observation	Factors Affecting Employees' thermal Satisfaction: • Nature (hot or cold) • To change the thermal conditions • Behavioral adaptation: changing clothes, controlling HVAC systems • Thermal pleasure.
(Karjalainen, 2007)	✓	interview	An experiment to disturb the ambient temperature	• Women are more dissatisfied with temperature than men. • Women prefer higher temperatures during the colder times of the year.
(van Hoof et al., 2010)		Semi-structured interview		• Consider a more limited temperature range in the hot and cold times of the year. • Observing the safety aspect of devices. • Proper location of outlet valves of devices for uniform temperature distribution.
(Strengers, 2008)		interview		Changing expectation for comfort leads to changing needs and energy consumption.
(Isaksson & Karlsson, 2006)	✓	interview	Environmental measurement and Questionnaire	• Assess people's desired approach to heat their homes. • Higher thermal satisfaction with middle floors. • The need to increase the accuracy of the thermostat degree.
(Karjalainen & Koistinen, 2007)		Interview		• Employees' dissatisfaction with uncontrolled and pre-planned air conditioning systems. • Inadequate temperature adjustment of systems with the number of employees.

Source	Method			Achievement
	Mixed	Qualitative	Quantitative	
(Brunsgaard et al., 2012)	✓	interview	Environmental measurement	• Educating employers on how to adopt the right approach to achieve a comfortable interior space. • Paying attention to the occupants' lifestyle and behaviors. • Solutions to adapt users to the summer heat.
(S. S. Shahzad et al., 2013)	✓	Semi-structured interviews	Questionnaire, environmental measurements	• The importance of "thermal environmental intention" and qualitative methods to question "neutral heat sensation". • "Neutral heat sensation" does not guarantee thermal comfort. • Prepare a graphical method to express user perception of thermal conditions.
(Wilhite et al., 1996)		Interview		• Investigate cultural distinctions. • Japanese families tend to heat just one room while Norwegians prefer to heat all.

6. CONCLUSION

This study examines different methods of thermal comfort research by comparing the philosophical foundations of the methodologies. Hence, it first introduces the ontology, epistemology, and methodology of common quantitative and qualitative methods. Then, through the gap found among current thermal comfort studies, the authors use an analytical review approach for investigating the existing research and their dimensions. Given the remarkable history of this research, comparison and analysis of the foundations of thermal comfort methodology can inspire the design of future research.

Methods should not be considered neutral tools which are selected and used arbitrarily. The study method is selected respecting compatibility among ontological, epistemological, and methodological assumptions which depend on and are linked to each other. Qualitative and quantitative methods take "reality" and "knowledge" from different points of view. Quantitative researchers believe that all affairs can be studied quantitatively. While qualitative researchers argue that the qualitative study of affairs, which can be inherently interpreted, prevents us from a profound look. In addition, quantitative researchers claim that explanation without measurement is baseless and useless until concepts of a theory are not examined experimentally. Therefore, in this approach, the study is regarded as an objective, organized, and formal process, in which numerical data are used to quantify phenomena and achieve results. Quantities consider ontological and epistemological foundations applied to natural phenomena to be applicable to human phenomena. While quantitative studies search for cause-and-effect relationships, the test of hypothesis, prediction, and control, qualitative studies seek to answer "why and "how". Qualitative studies aim to develop a theory, clarify the complexities of a phenomenon, and illuminate concepts and experiences. Therefore, qualitative studies basically rely on perception and argument.

Thermal comfort is considered one of the phenomena involved with human life, which assures their survival and life comfort. The complexities of thermal comfort studies are related to human aspects that are not regarded as convenient. Since humans have different schema due to their special socio-cultural backgrounds, this schema and presence in the environment provide different and highly-complicated perceptions which are affected by various factors. Therefore, the human knowledge and perception of thermal comfort conditions are extremely different. In addition, to know human perception, thermal comfort studies should know the contextual life of humans which is achievable through qualitative methods. Furthermore, using methods such as grounded theory and content analysis via in-depth interviews can be useful. After detecting the type of perceptions and its determining factors, quantitative methods can be used to test these theories. By relying on the fully-understood meaning of thermal comfort in a specific context, the use of mixed methods can increasingly assure readers to apply results of studies.

Qualitative methods have been less used in thermal comfort studies perhaps because of the dominance of quantity in current science, unfamiliar qualitative methods with time-consuming, and difficult implementation. Qualitative study cannot be defined easily, but with enough knowledge. Therefore, more studies should be conducted in different aspects of thermal comfort to theoretically saturate it.

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