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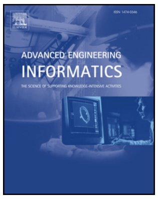

Full length article

Benchmarking thermoception in virtual environments to physical environments for understanding human-building interactions

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ABSTRACT

Thermal comfort influences occupant satisfaction, well-being and productivity in built environments. Several decisions during the design stage (e.g., heating, ventilation, air conditioning design, color and placement of furniture, etc.) impact the building occupants' thermoception (i.e., the sense by which animals perceive the temperature of the environment and their body). However, understanding the influence of design decisions on occupant behavior is not always feasible due to the resources needed for creating physical testbeds and the need for controlling several contributing factors to comfort and satisfaction. Virtual environments (environments created with virtual reality technology) are novel venues for studying human behavior. However, in order to use virtual environments in the thermoception domain, validation of these environments as adequate representations of physical environments (built environments) is imperative. As the first step towards this goal, we benchmarked virtual environments to physical environments under different thermal stimuli (i.e., hot and cold indoor air temperature). We identified perceived thermal comfort and satisfaction, perceived indoor air temperature, number and type of interactions as markers for the thermoceptive comparison of virtual and physical offices. We conducted an experiment with 56 participants and pursued a systematic statistical analysis. The results show that virtual environments are adequate representations of physical environments in the thermoception domain, especially for subjective perceived thermal comfort and satisfaction assessment. We also found that the type of first adaptive interactions could be used as the markers of thermoception in virtual environments.

1. Introduction

Occupant-building interactions are complex, multi-layered and influence both the environment and occupants [1]. These interactions, defined as any response of an individual or groups to their environment [2], are hard to predict due to the stochastic nature of human behavior [3]. Yet, occupants' interactions with building systems and elements and occupant related factors (e.g., behaviors, preferences) substantially influence satisfaction and comfort, as well as a building's energy consumption [4,5]. One of the most comfort- and energy-influencing interaction type takes place in the context of thermal comfort (e.g., interaction with heating, cooling, ventilation devices). Thermal comfort is defined as the state of mind that reflects satisfaction with a thermal environment and is usually assessed through subjective evaluations, such as thermal vote assessments in physical environments [6]. There are many contextual factors that affect occupant behavior [5,7]. Several decisions, made during the design stage of a building (e.g., control options, interior design, space orientation), influence occupants' thermoception (i.e., the sense by which animals perceive the temperature of the environment and their body). Due to the limited resources for testing the influence of such contextual variables on comfort and satisfaction, it might not always be feasible to use physical mock-ups during the design stage of a building in order to assess the impact of decisions on occupant's thermoception. However, virtual environments (environments created with virtual reality technology) could provide unique opportunities to construct such variables easily and relatively inexpensively. This could facilitate various occupant behavior studies in built environments for unbuilt spaces or for existing spaces that go through renovations. Obtaining the micro-level information regarding occupant behavior could be used in user-centered designs or user-centered building operations [2].

In order to collect thermal behavior data in built environments,

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there exist two contemporary methods [9]: creating acclimatized climate chambers, which provide experimental control and increased internal validity [8] and using real buildings as test beds, such as in [9,10] and [11]. The former method might not provide the mundane realism due to the lack of contextual factors, which do exist in real settings [12]. In addition, not many design teams have access to climate chambers to test their design decisions. Data collection in real test beds is advantageous for providing the realism with 'real occupants' and 'real office environments' with contextual variables and for long-term studies to understand temporal factors' influences on the thermoregulation behavior. However, the drawback is physical mock-ups have to be built to test different design decisions during the design stage, which is prohibitively expensive and, in many cases, might not be feasible. As de Dear et al. mentioned, in the past 20 years, neither method has been used as frequently as comfort simulations due to the growing availability of simulation tools. Yet, these simulation studies mostly lack the ground truth (i.e., lack of human subject data) [9].

Virtual environments provide an egocentric multimodal sensory (i.e., visual, haptic, auditory, olfactory, thermal, gustatory) [13] experience to humans wherein visual, auditory and kinesthetic aspects are defined by computers [14]. Humans are immersed in virtual environments wherein their perceptual systems interact with a simulated synthetic information through displays. This synthetic information is conveyed to the users through their perceptions as if it were real; this information envelopes them perceptually while continuous streams of stimuli are present [15]. Virtual environments have been widely used in many disciplines where human experience is in the foreground (e.g., social psychology [13], medicine [16], education [17] and training [18], design [19,20] and engineering [21]. These environments provide experimental supremacy in mundane reality in situ controlled experiments to isolate the exogenous factors and stimuli to transfer behaviors observed in virtual environments to the physical environments. Thus, virtual environments are alternative venues for human behavioral studies as controlled scenarios could be created and tested relatively easily [13] and in many cases cost effectively compared to physical mock-ups, especially in the case of built environments.

There exist several human-centered experimental studies in physical environments for understanding and improving occupant thermal comfort (e.g., [22–25]). However, integrating thermal cues (through thermoception) to virtual environments for understanding occupant behavior and improving perceptual realism in virtual environments have not been well studied yet. Realistic virtual built environments could potentially enable us to test different design decisions, such as the impact of changing the orientation of an office and the interior design or the material properties of objects (walls, furniture, etc.) on occupants' thermal comfort. Thus, the objective of this study is to benchmark virtual environments to physical environments with regards to thermal stimuli, by comparing users' perceived thermal comfort and satisfaction. We conducted a human subject experiment in an acclimatized hybrid environment where we recorded participants' (physical, psychological) responses when interacting with heating/cooling remedies. In order to understand the adequacy of using virtual environments in the thermoception domain, we compared participants' thermal comfort and satisfaction between virtual and physical offices. The paper is organized as follows. Section 2 provides an overview of thermal comfort and satisfaction in built environments. Section 3 reviews relevant studies conducted in virtual environments. Section 4 provides details of the research methodology. The results of the study and discussions are provided in Section 5, followed by Section 6, which conveys the limitations of the present study and presents future research directions. Finally, Section 7 concludes the study.

2. Thermal comfort and satisfaction

Thermal comfort influences overall occupant satisfaction, well-being and performance in built environments [26]. Humans regulate their body temperature through physiological responses, which are autonomous responses mediated by the sympathetic nervous system, as well as behavioral responses through coordinated and voluntary motor activities [27]. Cabanac defined the 'thermoregulatory behavior' as the control of heat gain/loss by adjusting the thermal characteristics of a physical environment through different means [28]. The motivation of these responses is the subjective feeling of satisfaction with a thermal environment [28,29]. During the process of perception, our senses capture environmental information (e.g., temperature stimuli). A strong enough stimulus transmitted to the brain results in a physical response, which is called 'behavioral temperature regulations' by Candas and Defour [30]. Under cold and hot conditions, physiological (e.g., redistribution of blood and increased/decreased metabolic heat production [31]) and psychological responses (e.g., tolerance of existing thermal condition and/or adaptation to such condition [32]) take place [33]. These responses mediate adaptive physical responses [34] through the above-mentioned neurophysiological perception path. Thus, it is important to study occupants' thermally adaptive physical responses, such as adjusting fans and heaters, thermostats, opening/closing windows and doors [35,36]. A previous study also highlighted the increased recognition of occupant interactions with building systems as an important determinant of thermal comfort and satisfaction. Thermal sensation and comfort have been frequently measured through subjective thermal votes (e.g., ANSI/ASHRAE, Bedford) derived from different thermal sensation models (e.g., predicted mean vote (PMV), dynamic thermal sensation (DTS)) [37–40]. However, these models and sensation scales vary in many aspects [41]. A previous study reported that most people do not perceive the categories of these subjective scales as equidistant. Thus, they concluded that the use of these subjective scales alone is not sufficient to understand human thermal comfort and sensation. The authors recommended the use of multi-dimensional measurement methods, such as objective measurements including physiological and behavioral recordings with subjective votes to understand occupant thermal comfort [42]. Glicksman and Taub also concluded that comfort models could be improved by better understanding occupant interactions and comfort state [43]. Thus, in addition to using the subjective votes, in the present study, we also used objective metrics (e.g., number and type of adaptive interactions).

Occupants feel more satisfied when they have more control over heating-cooling systems [44–47]. Previous studies compared personalized conditioning systems (e.g., personal control over local convective and radiant heating/cooling remedies) to conventional cooling systems (e.g., centrally controlled HVAC systems) and showed equal or better thermal comfort with personalized systems [37,48–52]. In addition, a previous experimental study confirmed that local thermal stimulation could influence the global thermal perception [38]. Thus, in the present study, we provided a mixed experience of personalized and conventional heating/cooling for thermal comfort. There are various comfort determinants, which increase the complexity of thermal comfort [39–42,53–55]. Although the first steady state thermal comfort model (i.e., Fanger's model) [56] is commonly used as a thermal environment design criteria and an objective measure in experimental studies [25], an increasing number of thermal comfort field studies (in physical environments) show that it is not always a good predictor of actual thermal sensation [57] as it does not address the personal thermal preferences and related decisions (as in physical interactions) [58]. Existing models' (e.g., [56]) limitations to capture and integrate the individual differences resulted in inaccurate estimation of occupant comfort and led to more human-centered modeling approaches [59–61], permitting direct measurements of perceptions (e.g., [62–64]). Thus, in this study we pursue a human-centered approach for benchmarking thermoception in virtual environments to physical environments through direct measurement of perceptions, and their adaptive consequences (i.e., decision such as physical response to environments through adaptive interactions).