I Want It That Way – Thermal Desirability in Shared Spaces

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ABSTRACT

Building management systems in commercial spaces commonly operate on predefined temperature setpoints and control schedules. These systems typically do not consider the individual occupant's thermal preferences, which often leads to high thermal dissatisfaction rates, especially in shared spaces. Recent studies target human-in-the-loop personalized control, where each occupant's thermal preferences are taken into account. These control systems require occupants to frequently submit votes regarding their thermal comfort. Such votes are usually acquired using surveys with standardized scales. However, occupants often find these too cumbersome or literally do not understand the questions.

This paper presents an intuitive thermal desirability scale to assess occupants' thermal comfort in scenarios with frequently queried feedback or control applications. The scale was tested in a survey with 100 participants against three common standardized thermal comfort scales. Results show that the thermal desirability scale provides a finer-grained understanding of control options for occupants than using a single standardized scale.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; *Empirical studies in ubiquitous and mobile computing*; • **General and reference → Empirical studies**; • **Applied computing** → Architecture (buildings);

KEYWORDS

indoor environmental quality, thermal comfort, building control, occupant feedback, human-in-the-loop, shared spaces

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1 INTRODUCTION

Thermal comfort, the satisfaction of an occupant with their thermal environment [1, 6], is an important factor in building control as it significantly influencees an occupant's health, well-being, and productivity [7]. This is particularly challenging in shared spaces, as control options are typically limited and many occupants have to share one thermostat. Instrumented spaces, i.e. spaces equipped with sensors, actuators, and controllers, have allowed research to focus on data-driven approaches that target the improvement of an individual's comfort — rather than an averaged cohort comfort [3, 9, 11]. These data-driven approaches rely on frequent occupant feedback: subjective votes describing an occupant's comfort regarding their thermal environment. Studies typically use international standards, such as ISO 7730 or ASHRAE 55 [1], or regional standards, e.g., EN 15251:2007 [8], and standardized scales to acquire occupant feedback. These standardized scales provide a snapshot of an occupant's thermal preference, the occupant's overall desires are often overlooked. Occupants often perceive these scales and questionnaires as cumbersome due to their length or confusing wording and voting consistency and reliability decreases. In order to put thermal votes into context, a deeper understanding of control and complaint behavior in shared spaces is necessary.

This paper presents the results of a survey conducted to gain a deeper understanding of occupant behavior regarding thermal desirability. Here, thermal desirability is defined as *an occupant's preference regarding their environment's temperature*. The main research objective is to understand how occupants perceive different comfort scales. A 5-point thermal desirability scale is presented and tested against existing standardized scales. The results are relevant for temperature control systems that require frequent votes.

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2 RELATED WORK

ASHRAE's thermal sensation, satisfaction, and preference scales are among the most popular and commonly used tools to estimate an occupant's thermal comfort with the goal of controlling a space's temperature [1]. The 7-point thermal sensation scale aims at measuring how an occupant feels thermally, with options from *cold (-3)* to *hot (+3)*. The 7-point thermal satisfaction scale evaluates how satisfied an occupant is with their thermal environment: *very dissatisfied* (-3) to *neutral* (0) to *very satisfied* (+3). The 3-point thermal preference scale provides control information, whether an occupant wants it *cooler* (-1), *no change* (0), or *warmer* (+1).

Approaches, such as [16], use ASHRAE's thermal sensation scale to collect occupant feedback as input for the PMV model to define actuation commands. The researchers have shown that using feedback systems in thermal control improve occupant satisfaction and energy savings overall. Recent research in the temperature control domain target data-driven models based on occupant votes to predict occupant comfort [9, 11, 12].

These approaches, using occupant triggered votes, have resulted in greater occupant satisfaction as compared to static set-point temperatures. However, there is an ongoing discussion and discrepancy among researchers which voting scales to use in feedback systems. Researchers have not yet agreed on a standardized mapping of the different scales and studies seldomly apply all three scales, which can lead to misunderstandings between occupants and researchers. For instance, a person may feel *warm*, but be satisfied (*neutral*), which would be an indication for *no change* of the thermal environment. In practice, thermal sensation options *slightly warm* (1) and *slightly cool* (-1) are often treated as *neutral* (0), due to the little change information that is enclosed [5]. Others map *slightly cool* (-1) to a *warmer*, and *slightly warm* (1) to a *cooler* preference [13]. There are seven answer options (-3 to +3) in the thermal satisfaction scale, such that the answer could be on either end of *warmer* or *cooler*. The thermal preference scale — with only three options — is not sensitive enough to allow for an accurate indication of the strength of the occupant's desire for control. A *warmer* vote would give no indication whether the temperature should be raised by, e.g., 1°C (2°F) or 5°C (9°F). Data-driven control models solve this actuation amplitude correction issue by querying occupants for frequent feedback, however, more sensitive response data would allow for better results.

Kim et al. presented a comparison of 14 studies according to the thermal comfort scales that studies used to generate personal comfort models [11]. Their comparison shows that 50% of the reviewed studies use ASHRAE's thermal sensation scale to generate predictions, with the ultimate goal for personalized control. None of the reviewed studies uses a combination of scales, although five studies apply reduced and adapted ASHRAE scales.

Some studies address these discrepancy issues by using non-standardized custom scales, adapted from existing scales, but do not verify the validity of their scale, compared to standardized scales. In a study, Francis et al. used a custom 5-point scale (*uncomfortably warm/cold*, *slightly uncomfortably warm/cold*, *comfortable*) to generate temperature setpoints [9]. Li et al. argue for a reduced 7-point sensation scale and applied an adapted 5-point sensation scale (*cold*, *cool*, *ok*, *warm*, *hot*) in combination with ASHRAE's thermal preference scale in their study [12]. Jazizadeh et al. [10] argue for a slider-based 10-point preference scale using guiding features, which resulted in a better voting consistency.

These studies lack a concrete mapping to existing scales, a translation for existing systems, a verified intent behind the wording, and do not address the applicability of the used scales. Without direct communication with the occupants, these issues can only be identified when using a combination of the scales, which these studies omit, as surveys containing all or a smaller subset of these scales would be time-consuming and too cumbersome for occupants. Further, participants of thermal comfort studies have issued the concern of being unsure which option to choose.

This paper addresses these problems. It presents and assesses a new 5-point thermal desirability scale, based on Bedford's scale [2]. The scale has been specifically designed for real-time human-in-the-loop thermal control systems with usability in mind [14] to allow for rapid responses by occupants.

3 THERMAL DESIRABILITY SCALE

The thermal desirability scale asks the occupant "*I want the temperature to be ...*", with five response options: *much cooler*; *slightly cooler slightly cooler*; *as is, I am comfortable*; *slightly warmer*; *much warmer*. The thermal desirability scale uses intuitive wording and combines the intent from the aforementioned existing standardized scales into one question. Since this ensures a quicker response from participants, its main intended use are time-critical feedback systems, whenever participants are reluctant to vote frequently, or when the sole purpose is control. Figure 1 shows the proposed mapping between ASHRAE's standardized scales and the thermal desirability scale, including the categorical response encoding.

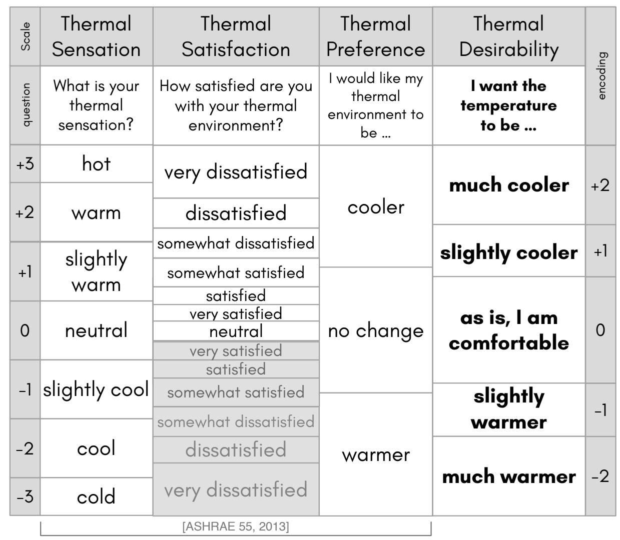


Figure 1: Mapping of ASHRAE's standardized scales to the thermal desirability scale.[1]

4 VALIDATION

A survey with 100 participants was conducted in July 2020 for gaining insights to the research questions posed above.

4.1 Design

The survey included 18 questions. It was conducted and distributed within an academic environment at the Technical University of Munich. Participants were asked to base their answers regarding shared spaces on their experiences before the SARS-CoV-2 outbreak, as at the time, many were working from home.

To test the thermal desirability scale against existing standardized scales, the survey was designed so that each participant was asked – among others – all four questions from Figure 1 in a randomized order. Participants who had no background in thermal comfort research were sampled to eliminate bias toward the scales. The participants were also asked about their amount of time spent in shared spaces (study space, computer room, meeting room, office, open office)[2], thermal control behavior, general thermal satisfaction, and smart devices. They were also asked to state their gender and age group.

[1] The answer options for thermal satisfaction could be on either end of the mapped scales, thus, duplicates are greyed out. *Somewhat Satisfied* and *Somewhat Dissatisfied* may also be mapped to *0*, *neutral*, *no change*, or *as is (comfortable)*.

[2] The participants were asked to relate all subsequent answers to their most frequently used shared space as stated in this question.

4.2 Results

The survey received 100 valid responses (63 males, 32 females, 3 diverse, 2 n/a). 90% of all participants were in the age group between 18 and 30 (25 between 18-21, 35 between 22-25, 30 between 26-30, 8 between 31-35, 2 between 36-40).

4.2.1 Satisfaction & Control Demand. 40% of participants were *somewhat dissatisfied* (26%) to *very dissatisfied* (4%) with the thermal environment in their most frequently visited shared space, while 21% felt *neutral* and 4% felt *very satisfied*. Table 1 shows the type of control means present in the participants' shared spaces. 44% of participants stated that the thermal conditions were controlled by mutual agreement, 28% were unsure. 47% listed a smartphone as preferred means of control, while 35% prefer manual control, e.g., a wall regulator. 9% would prefer no control (automatic).

Current control	[%]	Preferred control	[%]
Mutual agreement	44	Smartphone	47
Automatically	18	Manually	35
Dedicated person	4	Laptop	7
Unsure	28	Tablet	2
Other	6	None	9

Table 1: Current control and preferred means of control.

4.2.2 Scale Comparison. The scales were compared against each other, see Figure 2, to analyze the participants' understanding of each scale and to evaluate the convergent validity. Thermal preference correlates with thermal desirability, with a Spearman correlation of 0.76. The correlation between thermal desirability and thermal satisfaction (0.46) and sensation (0.48) is moderate. The correlations among the three ASHRAE scales are all below 0.39 (weak). For the overall reliability, the Cronbach's alpha [4] value revealed $\alpha = 0.77$ and for all standardized scales $\alpha_{ssp} = 0.66$.

Figure 3 compares the voting consistency of the three ASHRAE scales against the thermal desirability scale. The distribution shows that there is a discrepancy of votes regarding an 'intuitive mapping', e.g., a *satisfied* sensation would logically be mapped to *comfortable* or *no change*. For thermal sensation, 38% of participants who felt *comfortable as is* also voted for a *neutral* sensation, while 35% and 27% stated warm or cold sensations, respectively. Regarding thermal satisfaction, 42% chose a *slightly cooler* temperature, but only 17% of those stated some thermal dissatisfaction. As for thermal preference, 50% would have preferred their thermal environment to be *cooler*, with 72% choosing *slightly cooler* regarding thermal desirability, and 18% *much cooler*.

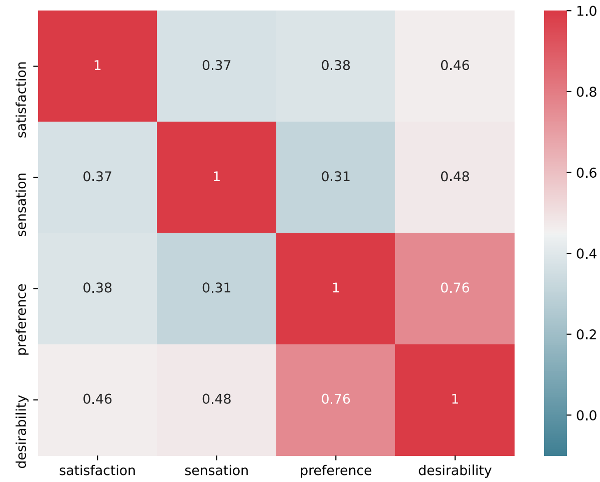


Figure 2: The correlation heatmap shows a correlation between thermal preference and thermal desirability.

5 DISCUSSION

The results indicate that occupants are aware of their general satisfaction and available control options. Most prefer the ability to control over no control, preferably using a technical device. The high dissatisfaction rate of 40%, in accordance with available and preferred control means indicates a need for fairer control systems with a focus on occupant interaction and usability.

The correlations and α confirm the assumption that using thermal sensation, satisfaction, or preference alone is not an adequate measure for thermal comfort, as the vote consistency varies between scales. Cronbach's alpha among the standardized scales indicates a discrepancy among votes. When cross-referencing voting consistency, e.g., 23% of non-neutral sensation votes did not prefer a change in temperature (Figure 3a) – a person may feel warm but be comfortable. This verifies that thermal desirability provides a better understanding of control preferences for occupants.

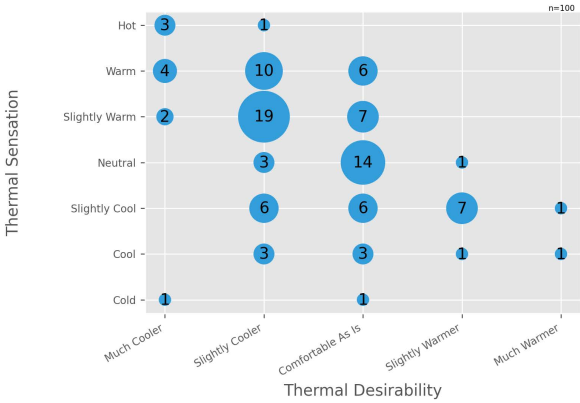
The correlation between thermal preference and thermal desirability confirms the need for a separation of control answer options, as shown by the distribution of, e.g., *cooler* votes against the thermal desirability options, where 72% of those would have preferred a *slightly cooler* temperature and 18% a *much cooler* temperature. This separation allows for a finer-grained assessment of overall preference regarding occupants' thermal comfort.

There are several threats to validity regarding the study design.

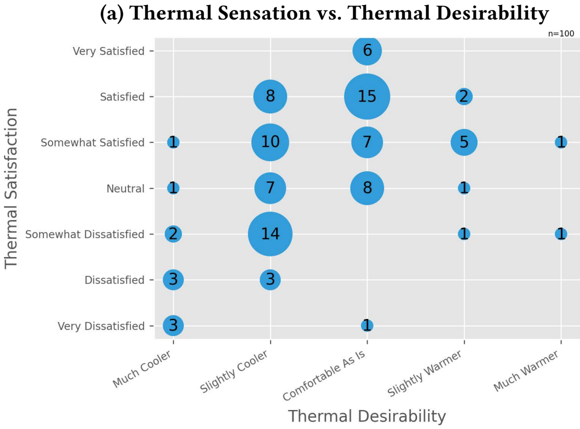
Internal Validity. The survey targeted the three most commonly used and standardized ASHRAE scales and did not take other scales, such as [2], into account, which introduces experimenter bias. Participants' perception of shared spaces was not fully accurate, due to the amount of time passed since they have worked under pre-SARS-CoV-2 circumstances, which – in most cases – involved a larger amount of people occupying a shared space.

External Validity. There was an uneven distribution regarding the age and gender of the survey participants which introduced a selection bias. The survey was conduced in summer within an academic environment in Munich, Germany, which are threats to representative sampling. The results are therefore representative only for a narrow demographic group; 100 participants are not enough to argue for significant results and an in-depth statistical analysis.

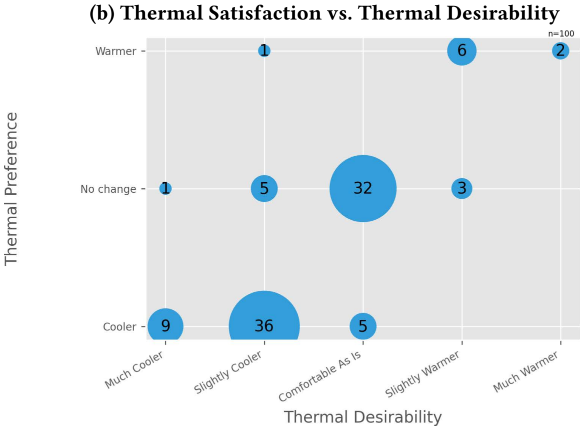
Construct Validity. Participants were asked to base their answers on their current environment's temperature to compare their individual answers regarding the scales. Since the survey was conducted in summer, the cross-comparisons showed an uneven distribution favoring cold preferences. In addition, some answers were contradicting and hint at confusion among participants regarding the questions. For instance, 5 occupants voted for *Comfortable As Is*,



(a) Thermal Sensation vs. Thermal Desirability



(b) Thermal Satisfaction vs. Thermal Desirability



(c) Thermal Preference vs. Thermal Desirability

Figure 3: Cross-referencing the thermal desirability scale against the three most common ASHRAE scales.

but a *Cooler* preference. More research into the language and reliability across votes is needed.

6 CONCLUSION

This work presents the 5-point thermal desirability scale to measure an occupant's preferences regarding thermal control, with respect to usability. It was validated in a survey with 100 participants. The survey contributed to a better understanding of perceived control preferences in shared spaces and showed that the thermal desirability scale may replace the use of standardized scales, such as [1]. When using the thermal desirability scale, it is recommended to provide rationale and explanations for each answer option upon the first introduction to the scale, to establish a common understanding among occupants and researchers and avoid misinterpretation issues. The thermal desirability scale does not provide a concrete mapping to temperature values as this would not account for individual preferences. Such temperature ranges should be established over time for each occupant individually, with respect to human-in-the-loop personalized control.

The thermal desirability scale remains to be tested during a control study to assess its reliability and effectiveness. A more detailed comparison to other scales during winter season and in different climates is required to further validate the presented results.

A persistent challenge is the actuation amplitude correction issue: Occupant responses need to be mapped to a concrete temperature to achieve an appropriate control effect. Existing approaches provide direction for control [13, 15], but tangible changes are unclear without asking additional questions. For personalized control, given the subjectivity of thermal comfort, a generally applicable concrete mapping is not possible. It remains future work to establish clear guidelines for concrete temperature mappings.

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