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Making Thermostats Great Again: Investigating Touch-Based Thermal Sensation for Manual Control of Thermostats

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ABSTRACT

While energy conservation is an urgent need, many people still misuse thermostats to control heating systems, resulting in wasted energy. One of the main causes is the lack of immediate thermal feedback. In this work, we investigate how immediate touch-based thermal feedback can be an appropriate interaction modality to improve the thermostat UI for manual control, and allow anticipation of the outcome of setpoint adjustment through user interaction. Based on two mixed-methods experimental user studies, we demonstrate the applicability of immediate thermal feedback to translate and anticipate a sense of thermal comfort that is meaningful and satisfying to the user. We also show the usability of this feedback as an interaction modality for adjusting a temperature setpoint, which is perceived as simple, natural and accurate.

CCS CONCEPTS

• **Human-centred computing** → **Interaction techniques; Interaction design.**

KEYWORDS

Thermal comfort, Feedback, Thermostat, Thermal perception

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1 INTRODUCTION

The operating principles of a thermostat and its elementary use seem fairly simple, they are not [16]. Research studies (e.g., [9, 12, 17, 18, 35]) highlight the need to improve the design and usability of thermostats as they play a crucial role [9, 27] in providing thermal comfort to occupants while limiting energy consumption, a growing concern since the energy crisis of the 1970s. In 2020, households account for 28% of total energy consumption in all sectors and space heating for 62.8% [10].

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A thermostat is a user interface (UI) for controlling a heating system, one of "*the most complex system in the domestic domain*" [35]. Day et al's conceptual model of the building interface [9] highlights this complexity as a heating system relies on multiple functional components and involves different levels of control and sources of functional feedback. This functional complexity is often reflected in the thermostat's UIs. The primary function of thermostats is to allow occupants to define thermal comfort by adjusting the temperature setpoint [1]. The heating system control logic then operates on a functional feedback loop, comparing the sensed temperature with the temperature setpoint to turn the heating on or off. Furthermore, the complexity of thermostat UIs has increased with new generations of thermostats [9, 35], including programmable thermostats, with ever-greater capabilities and features such as increased automation aiming at optimizing comfort and energy consumption levels.

The complexity of the heating system makes it difficult for occupants to understand the operation of the thermostat and the underlying automated control logic [9, 12, 17, 18, 35], resulting in an inaccurate User Mental Model of how the system works [18, 34] and of the cause-and-effect relationship between action and functional response [9]. By contrast, Karjalainen [17] and Peffer et al. [27] advocate for clearer and simpler thermostat UIs. Even with a good understanding of the underlying control logic, finding the optimum level of comfort and energy consumption is a multi-criteria decision task involving internal factors at the mental, physiological and physical levels, as well as external factors related to a transient thermal environment [18, 35], namely the delayed feedback. Psychological drivers (e.g., perceived loss of control, frustration when comfort requirements are not met), biological drivers (e.g., the need for thermal regulation) and social drivers (e.g., social norms) add to this complexity, leading to irrational decisions [9]. However, thermostats lack UI elements that help users anticipate the delayed feedback, neglecting the factors at play in the task [9, 17].

As a result of this functional complexity, the lack of usability of the thermostat's UIs [9, 12, 17, 18, 35] and inadequate interaction modalities [17, 36], occupants misuse their thermostat [9], wasting energy [9, 18, 26, 35] and negating the potential savings offered by automation [12]. In addition, despite the increased automation offered by programmable and smart thermostats, research shows that occupants still prefer to control the heating system manually [9, 12, 17], overriding the automated control decisions [12].

In this work, we focus on the immediate interaction between the occupant and the thermostat for the task of manually adjusting the temperature setpoint, and tackle the delayed feedback issue in thermostat UIs. Research and development of commercial products primarily focused on improving the core logic with automation and intelligence capabilities, and on adding novel features to the

UI (e.g. smart features), little research [9, 12, 26, 35] has been done to improve the UI capabilities of thermostats on this issue in particular [9]. To address the issue of delayed feedback in thermostat UIs, we investigate touch-based thermal sensation as an alternative modality for manual temperature setpoint adjustment. Using the thermal modality would provide a direct link between immediate feedback and functional delayed feedback in a more natural way. Indeed, research shows that to determine the state of the heating system, occupants often rely on other forms of feedback, such as thermal feedback as they often "*need for physical investigation, such as placing a hand over a radiator*", rather than visual feedback [36]. While the thermal modality has been successfully used to develop several interaction techniques (e.g., [31, 46]), to our knowledge, no previous work has investigated the thermal modality to address the issue discussed above.

To better understand how touch-based immediate thermal feedback for thermostat UIs could facilitate temperature setpoint adjustment and improve the design of thermostat UIs, we identify two critical points. The first is technical, in terms of producing relevant and meaningful thermal stimuli for users, and subsequently designing and implementing an appropriate interaction technique. The second is methodological, in terms of experimental evaluation of the interaction technique and the perception of thermal stimuli, which is multifactorial and subjective. In this context, we adopted a mixed-methods approach and conducted two user studies in laboratory-based controlled conditions, based on a proof-of-concept (PoC) thermostat prototype we implemented. This study aims to answer the following research questions:

- RQ1. Does touch-based thermal stimulus serve as immediate feedback for temperature setpoint adjustment, and how?
- RQ2. Does touch-based thermal stimulus serve as an affordance for adjusting the temperature setpoint, and how?
- RQ3. Is touch-based thermal stimulus a viable modality for the temperature setpoint adjustment task?

This work contributes in: (1) an understanding of how users experience touch-based immediate thermal feedback for the temperature setpoint adjustment task using a thermostat; (2) an implementation of touch-based immediate thermal feedback; (3) design implications with such feedback mechanism.

2 RELATED WORK

2.1 Expressing Comfort Preferences

In most existing thermostat models, expressing thermal preferences and comfort needs involves exclusively adjusting the setpoint. Early thermostat models often rely on mechanical knobs or sliders for this purpose [26, 36]. In more recent models featuring displays, users can press buttons or use rotary encoders to modify the temperature setpoint. Models equipped with touch screens progressively replace the physical input while keeping the same interaction technique.

One alternative approach involves the use of graphical widgets, such as sliders (e.g., [3]), or whole user interfaces (e.g., [48]) to enabling occupants a more direct way to express comfort preferences and needs. For instance, to replace the classical heating system UI, Clear et al. [8] designed a new web interface consisting of five buttons allowing occupants to express their current thermal comfort needs instead of specifying a setpoint to provide "*a dynamic view of*

comfort". In a commercial building, Winckler et al. [47] investigated a comfort voting system using a seven-point scale ranging from cold to warm. This system allows occupants to collectively adjust thermal comfort in work offices. Jensen et al. [14] proposed a new concept where rather than choosing a setpoint, users can choose a range of tolerable temperatures to better take advantage of variable electricity pricing and home thermal insulation. Vitali et al. [39] designed the Spell system, a touchable colour gradient ranging from blue ("*I'm cold*") to red ("*I'm hot*"), to enable occupants to express their current thermal sensation.

Another approach places users directly in the trade-off between thermal comfort and energy consumption through UIs. The TOP-Sliders widget [20] revisits traditional sliders for non-experts to explore a space of Pareto optimal solutions to find the best compromise between three criteria: financial cost, thermal comfort and indoor air quality. In SmartThermo, Alan et al. [3] displays the current electricity pricing and the estimated financial cost for heating alongside the chosen setpoint. Together, these studies show promising results when aligning the thermostat with its dual objectives of maintaining comfort and conserving energy through UI design.

2.2 Providing Feedback

Feedback plays a critical role in the use of thermostats and heating systems, a significance underscored in research [9]. Because of delayed thermal feedback, "*occupants may find [the thermostat] challenging to understand*" [9], namely the cause-effect relationship related to interaction. For instance, Karjalainen reports that "*most of the occupants have a false idea of the Celsius values of comfortable room temperatures*" [17]. In addition, while thermostat UIs must provide "*clear and sufficient feedback after adjustment*" [17], occupants have to cope with different sources of feedback [17, 36], at different temporalities, i.e. immediate and delayed, with different forms, i.e. natural and artificial.

Although being the main approach in current thermostat designs, occupants consider visual feedback the least practical method for thermostat use and the least appropriate for making system status intelligible. Additionally, more tangible cues such as air flow and clicking noise from the system, appears to be called on over visual and artificial feedback, e.g. icons on a display [36].

2.3 Thermal Stimulus-Based User Interfaces

Thermal sensation as a sensory modality for interaction is of recent development. Thermal sensation has been explored in various context to effectively convey information of diverse nature.

It has been employed to enhance digital media [23, 24], evoke and affect emotions in affective UI [2, 11, 21, 37, 46], and enable eye-free and non-intrusive GPS interaction [41]. Our focus lies within studies utilising thermal sensation specifically to convey environmental temperature information.

For instance, it has been used in many virtual or augmented reality (AR/VR) applications to enhance the immersion experience. In [5, 31–33], all used a modified Head Mounted Display (HMD) with special modules to provide thermal stimulus on the facial or neck area to enhance user's experience in virtual environments with different thermal conditions. Outside of AR/VR applications, "*Rain-Sense*", developed by Poguntke et al. [19], relies on wrist mounted

devices which provides thermal stimulus to communicate weather information. Together, these studies demonstrate the feasibility of using localised thermal stimuli to convey environmental thermal information which can impact the body sensation, either independently or in tandem with visual cues.

Regarding the design of thermal sensation enabled UIs, Wilson et al. have been studying augmented UIs with thermal feedback since 2011 and have uncovered several design requirements [42, 44–46]. The authors recommend using temperatures ranging from 22°C to 38°C with a neutral skin temperature of 30°C to ensure safety and a reliable and comfortable perception of thermal sensations. The design of thermal icons must take into account several parameters [42, 43] such as the direction of thermal change, intensity, and rate of change to express different meanings.

2.4 Summary

Research shows that thermal feedback is a viable output interaction modality for different types of user interfaces but, to our knowledge, it has not been used for thermostat user interface design. Most interestingly, it seems to be feasible to use localised thermal stimuli to provoke whole body sensation.

However, beyond Vitali et al.’s exploration of visual stimuli for comfort perception [39], there is limited research leveraging thermal perception to express thermal comfort preferences. Moreover, thermostat UI design primarily relies on visual elements for feedback and feedforward. Apart from Van Oosterhout et al.’s study [38], which investigated force feedback and shape changes in thermostat interaction, few studies have explored alternative sensory modalities other than visual. Currently, thermal sensation as modality is not explored for thermostat UIs.

According to the Frogger Interaction Framework [40], which further explores Norman’s concepts of feedback and feedforward [25], interaction would be richer as action and reaction will coincide in *Time* thanks to an immediate thermal feedback as well as in *Modality* thanks to a touch-based thermal perception, local to the thermostat. Applying this framework helps to identify some of the causes of the feedback issues: a lack of strong coupling between the user’s action (i.e., inherent feedback) and the system’s heating function (i.e. functional feedback). Precisely, action and reaction do not coincide in *Time* (i.e., temporality discrepancy) due to thermal inertia and leading to delayed thermal feedback, nor in *Modality* (i.e., discrepancy between modalities) with a haptic sensation for action through the manipulation of thermostat’s controls combined with a thermal sensation in response.

3 METHODOLOGY

To investigate the effects of immediate touch-based thermal feedback on user interaction for the temperature setpoint adjustment task, we designed and conducted a laboratory-based controlled experimental study using mixed methods.

Our approach targets thermal stimuli representative of the thermal comfort level associated with the selected temperature setpoint. Thus, thermal stimuli should act both as immediate feedback, confirming the desired level of thermal comfort, and as feedforward, providing an indication of the ambient thermal sensation to come later in the room.

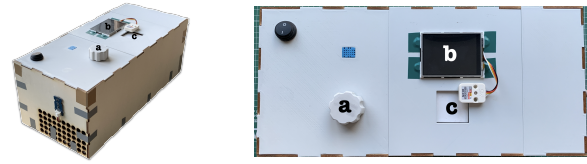


Figure 1: Main UI components of the prototype thermostat: (a) Rotating knob/button, (b) LCD screen, (c) Peltier module.

To this end, we have designed and developed a thermostat with a tangible user interface as a proof-of-concept (PoC). Our PoC allows participants to perceive tactile thermal stimuli as they adjust a temperature setpoint. Based on a mobile heater controlled by our PoC, ambient thermal feedback is generated according to participant’s chosen temperature setpoint.

Regarding our research questions highlighted in introduction, we formulated the following hypotheses concerning the effects on user interaction when using our PoC:

- H1: *Perception*. Participants perceive touch-based thermal sensation as immediate feedback in the setpoint adjustment task.
- H2: *Action*. Participants rely on immediate touch-based thermal sensation to achieve the setpoint adjustment task rather than delayed feedback.
- H3: *Association*. Participants interpret immediate touch-based thermal sensation as an indication to subsequent global thermal sensation.
- H4: *Performance*. Immediate thermal feedback has an effect on: (a) Number of adjustments: participants require few adjustments; (b) Comfort level: participants do not choose extreme setpoints likely to cause thermal discomfort.
- H5: *Perceived usability and efficiency*. Participants find easier to adjust the temperature setpoint with higher precision compared to their past experience with thermostats.

Our experimental design consists of a preliminary study, conducted during winter 2022, followed by a within-subject experiment, conducted during winter 2023. The preliminary study involves two phases: (1) the calibration of thermal models implemented in the PoC using a trial-and-error approach; (2) a pilot experiment to validate the calibration of thermal models, and to test the protocol and questionnaires of the experiment, and subsequently to obtain early data. The pilot experiment and the within-subject experiment are composed of three phases: a pre-study questionnaire, an in-study evaluation with the PoC, a post-study questionnaire including an interview.

4 PROOF-OF-CONCEPT: IMPLEMENTATION

As shown in Figure 1, we implemented our PoC as a tangible thermostat device composed of: a clickable knob; a thermal touchpad capable of producing a hot or cold sensation; a temperature sensor to measure skin temperature; and a small display (approximately 10 cm x 15 cm).

4.1 User Interaction

To adjust a temperature setpoint, the user interaction consists in placing a finger on the thermal touchpad with one hand and then turning the knob with the other hand. Although the thenar eminence’s

area [42] is hand’s area showing greatest sensitivity, we chose fingertips because users primarily interact with thermostats using their hands, especially their fingers, and because they have been found to be viable for the material discrimination task with thermal displays and real material [15].

Turning the knob changes the value of the setpoint temperature: turning clockwise increases the value of the temperature setpoint; turning anti-clockwise decreases this value. Thermal feedback is then provided through the touchpad, aiming at providing an indication of the upcoming thermal sensation at body level. This thermal sensation is generated relatively to a neutral sensation to serve as thermal affordance and to guide the user while adjusting the setpoint. A linear scale with a moving cursor is displayed on the screen, representing a range of temperatures. Clicking the knob validates the selected setpoint, the ambient temperature is then controlled and maintained using a feedback loop that compares the temperature setpoint with the sensed ambient temperature to activate or deactivate the heater.

4.2 Hardware

The prototype is implemented using an Arduino Mega connected to: a 3.2-inch LCD display (*4D Systems uLCD-32PTU-PI*) with a resolution of 320×240 to display information; a *BME280* digital temperature sensor to measure air temperature; a *MCP9808* temperature sensor to measure skin temperature; a 12-volt *TEC1-12706* thermoelectric Peltier module driven by a *XY160D* motor controller module coupled to a *MLX90614* thermometer for precise control of the intensity and speed of the thermal stimuli produced by the Peltier module; a generic 360 rotary encoder with a 3D printed cap of 40 mm diameter. The Arduino Mega controls controls a 2000 Watt electric radiator through a DiO remote controlled plug (DiO 1.0, ref 54886) using a 433MHz RF emitter (FS1000A). The code is implemented using the Arduino programming language and broadly consisting of: (1) controlling the heater according to a feedback control loop as for a standard thermostat; (2) responding to user actions (i.e., clickable knob) by providing visual and thermal feedback based on formulas explained in the following sections; (3) safety measures such as limiting the temperature range of the Peltier module from 15°C to 42°C to avoid pain sensation [22].

4.3 Thermal Models

Local thermal stimuli has been explored in VR applications to convey whole-body thermal sensation [6, 28]. Our prototype adopts the same approach. In order to provide an indication of future global thermal sensation (i.e., at whole body level) from a local thermal sensation measurement, we use two thermal sensation predictive models based on the thermal sensation scale defined by ASHRAE [4], ranging from -3 (cold) to +3 (hot).

To predict local thermal sensation given a steady state thermal stimulus on the ASHRAE thermal sensation scale, we rely on Zang et al.’s model [49]. We chose to rely on steady state thermal stimuli as it allows us to use off-the-shelf components. Indeed, predicting thermal sensation under transient state thermal stimuli requires high precision and high frequency measurement of skin temperature. In addition, using transient state thermal stimuli to evoke a specific level of thermal sensation when touching needs high

precision control of the temperature change rate. To meet these requirement past studies (e.g., [7, 13, 30–33]) have used specific hardware and sophisticated thermal transfer models to predict thermal sensation in transient environment. Consequently, in terms of interaction, such an alteration means that the users could not touch the thermal touchpad until the target temperature is reached. Using a commonly found 12-volt Peltier module with adequate cooling, users are expected to wait up to 5 seconds.

To predict global thermal sensation, we rely on Rabbani et al.’s adjusted Predicted Mean Vote (aPMV) model [29] as our experimental setup is very similar to their and as they showed positive experimental results with the adjusted model. The PMV (Predicted Mean Vote) model [4] is widely used to predict global thermal sensation for a given setpoint. Rabbani et al.’s model refines the PMV model to improve alignment of thermal comfort predictions with user expectations.

In most studies on thermal comfort, the neutral sensation is considered equivalent to thermal comfort. We therefore use the neutral sensation as a reference point for the comfortable setpoint, thus providing thermal affordance for action.

5 PRELIMINARY STUDY

This preliminary study lays the groundwork for the experimental study. The goal is to (1) ensure that the thermal models chosen generate thermal feedback in line with users’ sensory perception, which involves identifying appropriate parameters and calibration method; (2) verify that the experimental setup works as intended; (3) design, test, and improve the experimental protocol, and ensure it produces usable data. The approach is both incremental and trial-error based. A total of 33 participants (study of local thermal model: 10, study of global thermal model: 14, pilot study: 9) were involved and all the participants were asked to sign a consent form. All the experimental sessions are conducted in light proofed, temperature controlled rooms with similar surface and volume with controlled artificial lighting.

5.1 Thermal Model Applicability

Local thermal sensation model. We evaluated the applicability of Zhang et al.’s model [49] (see eq. 1) experimentally. The prediction is based on the temperature difference between the local skin area (T_{skin}) and the contact surface ($T_{stimulus}$). Unlike prior studies, our implementation employs a broad and continuous range of thermal sensations rather than a limited set of predefined sensations.

$$Local = 6 / (1 + e^{-S_{skin} \times (T_{stimulus} - T_{skin})}) - 3 \quad (1)$$

We estimated $S_{skin} = 0.185$ in equation 1 ($R^2 = 0.816$), the parameter represents the thermal sensitivity of the skin, being a suitable value for the generation of touch-based thermal stimuli in line with participants’ perception of thermal comfort when touching. To achieve this, we collected fingertip temperature data from 10 participants, measured from the index and major fingers of their dominant hand. Participants then provided subjective thermal sensation ratings for a randomized sequence of 14 thermal stimuli, sensed using the same fingers. The sequence is comprised of 7 fixed temperature stimuli ranging from 21°C to 39°C in 3°C increments, each repeated twice. A 1-minute pause is done after each thermal

sensation vote is given. Temperature difference is then calculated from the collected data and used to fit. With data collected, we estimated S_{skin} parameter using non-linear least squares method¹.

Global thermal sensation model. Following an initial experimental study we carried out with nine participants to assess the applicability of PMV model alone², we chose Rabbani et al.’s adjusted Predicted Mean Vote (PMV) model [29] (see eq. 2). This model linearizes the PMV model for more individualised prediction. Drawing on the results of our initial experiment, we empirically included an individualised component in equation 2 to obtain a prediction of global sensation that is based users’ actual sensations ($Actual_i$) and the measured room temperature. In a trial-error experimental session with 5 additional participants, we estimated suitable values for parameters of equation 2: $a = 1.3$, $b = 4.75$ and $c = 0.1$.

$$aPMV(T) = a \times PMV(T) + b$$

$$Global(T) = aPMV(T) + c(Actual_i - aPMV(T_{room})) \quad (2)$$

Calibration process. Drawing insights from the preceding experimental studies, we devised a two-step calibration process. First, we complete the equation 2 by inquiring users’ actual sensation ($Actual_i$). Second, we measure the average fingertip temperature (T_{skin}) of the major and index fingers on both hands to establish and calibrate the neutral sensation using equation 1 for each participant.

5.2 Pilot of the User Experiment

To test and improve this experimental design and to verify the experimental setup works as intended (i.e., usability, hardware, and software including implementation of thermal models), we designed a threefold experimental study composed of: two questionnaires, one submitted at the beginning of the session (pre-study), and the other one at the end, coupled with verbal exchanges to gather subjective and qualitative data (post-study); (2) a user-centred evaluation of the interaction with the PoC (in-study). We then recruited 9 participants to conduct the experiment in a semi-realistic scenario. They were compensated with a 15 Euros gift card.

Participants are asked to use the PoC to find their ideal temperature setpoint in a room cooled to 16°C. Each participant underwent the calibration process. Following this, they used the PoC to test the touch-based thermal sensations of various temperature setpoints. Subsequently, they selected one setpoint and experienced the global thermal sensation after the room reached the desired setpoint.

We observed participants’ behaviors during setpoint adjustment and collected feedback on the accuracy of the mapping between touch-based and global thermal sensation they experience when interacting with the prototype. We noticed that some participants found their optimal setpoint after only one adjustment by comparing the touch-based sensation of various setpoints, while others needed multiple attempts to discover their ideal setpoint. 8 out of 9 participants found easy to find a satisfying setpoint thanks to thermal feedback. A majority of participants (6/9) were satisfied with the established mapping derived from the calibration process. However, a few participants (3/9) felt there was room for marginal

improvement in the mapping but found the discrepancies manageable during the prototype interaction session. We concluded that the current implementation of thermal models represents an acceptable compromise, offering adequate performance for most participants while maintaining comparability of sensation across all participants.

6 USER EXPERIMENT

Drawing on the preliminary study, we designed a within-subjects experiment to observe user behaviour with immediate thermal feedback and feedforward. The experimental design is composed of three phases (pre-study, in-study, and post-study) organised into two sessions. Participants underwent the two sessions employing our PoC: the initial session served as a baseline, without touch-based thermal feedback, followed by the second session incorporating it. In both sessions, participants carried out a setpoint adjustment task, manually controlling the thermostat to find their optimal setpoint. To reduce potential recall bias, we chose time-separated sessions instead of classical counterbalanced experiment design: participants attended the second session at least a week after the first (min: 6 days, max: 44 days, on average 18.85 days). In addition, the UI is intentionally designed to prevent users from memorizing specific setpoints, thereby avoiding any potential transformation of learned preferences between the two sessions.

6.1 Participants

In total 13 participants (9M/4F, average age 36.8) in good health condition were recruited for the user study conducted in winter 2023. Each participant received a 15 Euros gift card upon completion of the experiment. All the participants were asked to sign a consent form. The experimental setup is the same as the pilot study.

6.2 Procedure

For each session, participants were introduced in a room (approx. $15m^2$, $45m^3$) cooled to 14°C. The PoC’s GUI presents the temperature setpoints on an horizontal seamless linear scale without additional indicators of position or numeric values. In total 24 setpoints are available, corresponding to a 14°C–26°C range with 0.5°C increment. The numeric value of the setpoint and the corresponding temperature are omitted from the UI to prevent any potential bias towards a particular temperature and to encourage exploration.

During the pre-study phase, participants first complete a questionnaire to document their cloth level and the initial global thermal sensation in the room. Next, they are introduced to the prototype and were asked to roughly estimate a comfort setpoint range, relying solely on visual feedback in the first session, with immediate thermal feedback in the second. Participants are permitted to engage in non-physical activities, such as office work, during the waiting period of each session. During the in-study phase, participants have to complete the setpoint manual adjustment task to identify their ideal setpoint. A think aloud protocol is applied, participants are asked to verbalise each time they change the setpoint. During the post-study phase, a questionnaire is administrated once the ideal setpoint is identified by the participant.

¹https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html

²We chose the following values for other parameters of PMV model: velocity = 0.1, relative humidity = 0.4, metabolism level = 1, clothing level = 0.5

6.3 Data Collection

In order to comprehend user behavior and to evaluate our hypotheses, we collected quantitative and qualitative data in each session, including verbatim during and after the in-study phase.

During the pre-study phase, we collected two setpoints (min, max) defining the participant's rough estimate of a comfort setpoint range in order to quantify user's overshoot behaviour while adjusting the setpoint temperature. To do so, we calculate the relative position of participant's initial and final setpoints within their estimated comfort setpoint range³.

During user interaction (in-study phase), the thermostat prototype recorded each setpoint adjustment made during each session, and on all setpoints tested using touch-based thermal sensation during the second session. Additionally, verbalization explaining the reasons and methods behind setpoint changes were recorded, transcribed, and subjected to analysis.

The post-study questionnaire in the first session consisted of three open-ended questions probing participants' general strategies during the session, factors influencing their choice of setpoint, and whether and how they anticipated changes in thermal sensation after adjusting the setpoint. Additionally, three 7-point Likert scale items were included to assess the baseline usability and the influence of the UI on setpoint adjustment behavior. In the second session, two additional open-ended questions investigating how users perceived and used the touch-based thermal sensation is added before the three questions used in session 1, and five more 7-point Likert scale items were included to investigate user's perception on the correctness of the mapping between touch-based and global thermal sensation as well as their perception of the usefulness of the touch-based thermal sensation for the setpoint adjustment task in regards to easiness and precision.

7 RESULTS

7.1 Baseline Setpoint Adjustment Behaviour without Touch-Based Thermal Stimuli

7.1.1 Strategy. 4 categories of approaches emerged from participant's self reported strategies in the first session without the touch-based thermal stimuli: **Estimated-ideal** (P1, P2, P3, P4, P5): Participants select their initial setpoint based on an estimated ideal setpoint and then make subsequent adjustments based on the effective thermal sensation. **Increment** (P9)/**Decrement** (P6, P7, P10, P11): Participants deliberately choose a setpoint with the aim of undershooting/overshooting to ensure the room is not too cold/warm, and then make further setpoint adjustments to achieve the desired level of thermal comfort. **Dichotomic** (P12, P13): Participants start with the middle setpoint, then rely on the effective sensation as a reference to make further adjustments to find the desired comfort level. **Reversed search** (P6, P8): Participants are satisfied with the current sensation and adjust the setpoint to match the current condition. This strategy can be used in conjunction with the 'Decrease' strategy. Participants choose a high initial setpoint to activate the heater, wait for the room to reach the desired sensation, and then adjust the setpoint to match the condition in the room.

³ $P_{relative} = \frac{S_i - S_{mincomfort}}{S_{maxcomfort} - S_{mincomfort}}$

When asked what factors influenced their setpoint choices, participants often mention their sensation as the major factor (P1, P3, P4, P7, P9, P10), e.g., "I tried to base the adjustment solely on my feelings" (P1). Participants' think-aloud records of setpoint changes are coherent with their statement, e.g. "I increase the temperature because my fingers are a bit cold" (P7). Others cited the visual scale as the main factor (P2, P5, P12, P13), e.g. "I estimated [my preferred setpoint] by comparing the scale here and the scale of my heating system at home" (P2). P6 and P8 both cited heating status as the most important factor, critical to their strategy. Only P11 explicitly cited the comfort expectation as a factor in the choice of setpoint. Additionally, participants mentioned factors such as activity, clothing, impacting their setpoint choices during the session. These findings are consistent with the observations reported in [36].

7.1.2 Anticipation. When asked what factors they relied on to anticipate changes in sensation, many participants (P2, P3, P5, P11, P13) intuitively rely on the position of the setpoint they have chosen (e.g., "The minimum setpoint should correspond to the outside temperature with no heating, and the maximum setpoint should give the impression of a very hot summer" (P3), "the position of the pointer in relation to the centre" (P5)), or relied (P1,P4) the displacement of the setpoint ("Depending on how much I increase the setpoint" (P4)). The configuration (size/type of the heater, size of the room, number of people in the room) was also used to anticipate ("The ratio between the size of the heater and the size of the room" (P7), "I took into consideration the size of the room, the size of the heater [...] and the number of persons in the room" (P10)). Some participants (P6, P9, P12) simply did not attempt to anticipate the thermal sensation, and stated they adjust the setpoint as a reaction to their feeling rather than trying to anticipate (e.g., "Nothing, I estimated and then waited to feel before changing (the setpoint)" (P12)). P8 due to his particular strategy did not require any anticipation during the session.

7.2 Setpoint Adjustment Behaviour with Touch-Based Thermal Stimuli

7.2.1 Interpretation of Touch-Based Thermal Stimulus. All 13 participants understood the touch-based thermal sensation as an indication/prediction of comfort when asked how they interpreted the touch-based thermal sensation during the second session (e.g., "This (the sensation when touching) gives me an idea of the temperature I should feel after changing (the setpoint)" (P4), "The sensation is a prediction, I (change the setpoint till) touch the temperature I want it to reach" (P6)). While many participants (10/13) found the touch-based thermal sensation intuitive as an indication of further global thermal sensation, some participants experienced difficulties to extrapolate the local touch-based thermal sensation ("It's not that easy to transpose the sensation on my finger to the rest of my body" (P8), "It's not the same thing because it's a touch and not really the same thing as the ambient sensation" (P12)). Particularly P5 made the remark that when she tried several setpoints in a broad range and in rapid successions, the sensation seemed slightly different for her: "The initial setpoint feeling neutral feels slightly cold after trying my maximum comfort setpoint".

Regarding the mapping between touch-based and global thermal sensation, P1 and P9 initially expressed skepticism about whether touch could accurately represent global thermal sensation upon

reaching the setpoint. However, they expressed satisfaction with their experiences towards the end, ultimately considering the mapping accurate, e.g. "I was skeptical [...] but it turned out to be more correct than I thought" (P1); "I wondered about the link between the touch-based and (the global) thermal sensation, but it turned out to be a good match" (P9). Notably, a significant portion (9/13) of participants expressed very high satisfaction with the mapping ("1:1" (P6), "Identical" (P2), "Same sensation" (P3), "Very good correspondence" (P1), "Good correlation" (P5, P9, P10), "Very good relation" (P11), "It correspond" (P13)). However, some (4/13) participants felt the mapping was slightly off ("Very close" (P4), "The air feels ever so slightly cooler than when touching" (P7), "I felt slightly cooler when touching than in the air" (P8), "In the end, the air feels warmer than what was felt when touching" (P12)). These results tend to validate (H1)/(H5).

7.2.2 Effects of Touch-Based Thermal Sensation on Strategy. In the second session, we remarked that the thermal stimuli provided by the prototype played a prominent role in all 13 participant's self reported strategy: "The initial calibration allowed me to determine a comfortable setpoint range when touching. I chose the lowest temperature that suited me as the initial setpoint" (P1); "I chose a setpoint that was right for me, lower was too cold when touching, higher was too warm" (P6); "Thanks to the touch (sensation), I was able to test the feeling instantly, which allowed me to do several tests to calibrate it as good as possible" (P4).

When asked about the factors influencing the choice of setpoint, participants again all emphasized the touch-based thermal sensation. However we noticed participants aimed for different sensation when touching: some (P6, P9) explicitly aimed for neutral sensation (e.g., "By touch, aiming for a neutral setpoint" (P9)); some explicitly aimed for the minimal setpoint they can tolerate (e.g., "I chose the lowest temperature" (P1), "I started with a slightly higher setpoint and once I was happy with the (touch) temperature I lowered it a little" (P12)), or a comfortable setpoint (e.g., "I gradually increased the setpoint until I felt comfortable (when touching)" (P12), "In the end, I chose the comfort setpoint based on my feel for the plate" (P3)). The rest of the participants did not specify which sensation they were aiming for. These results tend to validate (H2).

7.2.3 Effects on Anticipation. In contrast to the first session, participants unanimously reported using the touch-based thermal sensation to anticipate the incoming thermal sensation change after a setpoint change. Most (11/13) relied exclusively on the touch-based sensation: e.g., "the comfort level of the touch [...]" (P2), "Just the touch" (P11), "The (touch) plate, even if it didn't help me find the right setpoint all at once [...]" (P12). Only P1 explicitly mentioned the displayed scale as a factor for anticipation ("[...] the amplitude of the change on the display [...]"), and P10 included whole body thermal sensation as additional factor to touch: "[...] the felt temperature in the room [...] the tension or not in my body [...]. My confidence in the accuracy of my (felt) fingertip temperature being what I needed was the biggest factor". These results tend to validate (H3).

7.3 Quantitative Analysis

All data samples discussed in this section were first subjected to a normality test before performing a paired t-test or Wilcoxon rank-sum test.

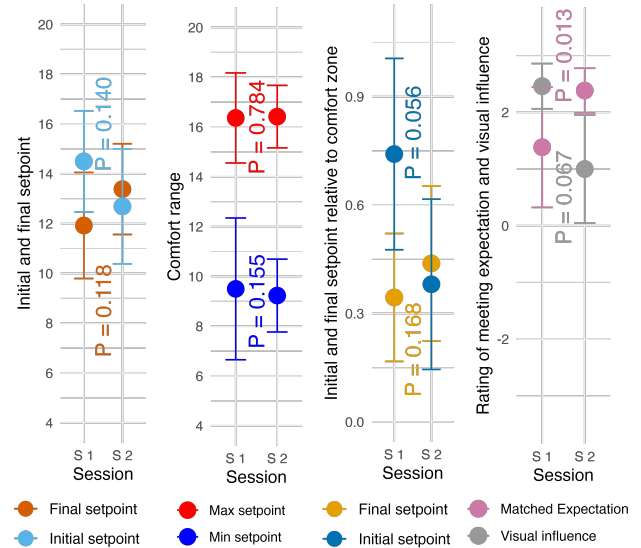


Figure 2: Mean and sd of the (left to right): (1) minimum and maximum setpoint on the scale (between 0 and 24) for estimated comfort range; (2) initial and final setpoint on the scale (between 0 and 24); (3) relative position of initial and final setpoint on the scale within the estimated comfort range (between 0 and 1); and (4) rating (-3 to 3) of final sensation in line with expectations, and visual influence on position selection. p-values are presented in a matching color.

In terms of general perceived usability and efficiency, we found no significant differences. However, we found a significant decrease of number of setpoint changes in the second session (S1: $M=3.31$, $sd=2.53$; S2: $M=1.38$, $sd=0.65$, $p=0.030$), indicating participants achieved their comfort goal with less setpoint changes. By comparing initial and final setpoint position (Figure 2-1), and participant's estimated comfort setpoint range (Figure 2-2), we found no significant differences. However, regarding the relative position of the setpoints within participant's estimated comfort setpoint range (Figure 2-3), we found that participant's initial setpoint is at a significant lower position (S1: $M=0.73$, $sd=0.46$, S2: $M=0.33$, $sd=0.55$, $p=0.056$), indicating participants are more conservative with their initial setpoint. Additionally, we found a significant difference in both relative setpoint change (S1: $M=-0.49$, $sd=0.74$, S2: $M=0.28$, $sd=0.84$, $p=0.029$) and absolute setpoint change (S1: $M=-2.69$, $sd=5.88$, S2: $M=0.69$, $sd=1.97$, $p=0.053$) between the two sessions, meaning participant's initial setpoint is further away than their chosen setpoint in session 1 than in session 2. This is an indication of an avoided overshooting behaviour in session 2.

We observed that in session 2, participants rated the final thermal sensation (Figure 2-4) as better than expected (S1: $M=1.39$, $sd=1.76$, S2: $M=2.38$, $sd=0.65$, $p=0.067$). We also observed a significant drop of subjective rating of the influence from the visual feedback from session 1 to session 2 (S1: $M=2.46$, $sd=0.66$, S2: $M=1.00$, $sd=1.58$, $p=0.013$). Additionally, participants rated the influence from touch-based thermal sensation ($M=2.15$, $sd=1.14$) significantly higher than

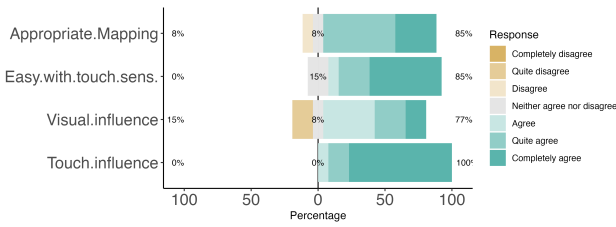


Figure 3: Participant’s rating of: the appropriateness of mapping between touch-based and global sensation, easiness to find a setpoint representative of comfort, visual and touch-based sensation influence on setpoint choice.

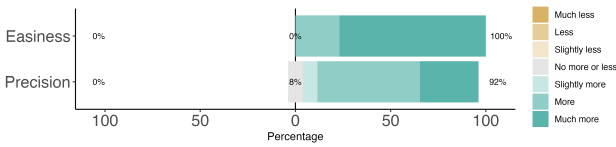


Figure 4: Participant’s rating of: easiness and precision of setpoint adjustment task based on thermal stimuli.

that of the visual feedback ($M=1.00$, $sd=1.58$) on the setpoint choice ($p=0.058$) in session 2.

When participants were asked whether they thought the touch-based thermal sensation and the global thermal sensation were a good match, they generally agreed with the mapping (Figure 3). Although there is no significant difference between the two sessions ($S1: M = 1.02, SD = 1.60$ $S2: M = 2.00, SD = 1.00$ $p = 0.943$) when comparing the perceived ease of use and efficiency of the prototype with regard to the setpoint setting task, when asked if the added touch-based thermal sensation helped, participants not only agreed that the touch-based thermal sensation helped, they also found that it made the setpoint setting task much easier and more accurate (Figure 4). These results tend to validate our hypotheses, including (H4).

8 FINDINGS & FUTURE WORK

This work demonstrates the applicability of immediate thermal feedback to convey a meaningful and satisfying sense of thermal comfort to the user, improving anticipation. The feedback is perceived as simple, natural, and accurate for adjusting a temperature setpoint, demonstrating high usability as an interaction modality.

A First-order stimuli. In line with Tamas et al.’s observations [36], tactile thermal sensation overcomes visual and other cues for assessing thermal comfort. All participants showed a clear shift from relying on a variety of cues in the first session to relying on touch-based immediate thermal feedback for strategies and anticipation in the second session. *Design implications:* to achieve an efficient and accurate assessment of thermal comfort levels, the UI should take advantage of thermal modalities.

An intuitive thermal comfort feedback (RQ1). Thermal comfort is clearly reflected by the thermal stimulus and was extrapolated at body level by most participants. The thermal stimuli, generated by the Peltier module using thermal models to align local thermal

perception with global thermal perception, were found to be objectively representative of thermal comfort levels when touching, to a lesser extent for some of the participants. Therefore, the approach of relying on local and global thermal perception models, calibrated for individual differences, to align local and global thermal sensations is promising. *Design implications:* due to the variability of internal factors (e.g., mood, health) and external factors (e.g., weather), the user interface should include a calibration task that can be performed regularly, as well as the measurement of skin temperature for each individual.

An affordance for adjusting temperature (RQ2). Thermal sensation scale is found to be a perceptible and usable affordance for adjusting temperature. Without thermal feedback, participants developed very different strategies for adjusting the setpoint, leading to significant differences between their initial and final setpoints, and required more setpoint adjustments. Thanks to the thermal scale, participants avoided extreme setpoints and made significantly fewer adjustments. All the participants reported they were able to anticipate the comfort level after making an adjustment with the touch-based thermal sensation. The representativeness of the mapping again plays a critical role. *Design implications:* the neutral point should be carefully chosen to be mapped to an appropriate temperature setpoint (e.g., 19°C) to meet user expectations.

A perceived simple and precise modality (RQ3). Touch-based immediate thermal feedback appears to be a suitable modality as participants found it usable, were able to interpret with precision the stimuli as a level of thermal comfort, and were satisfied with their setpoint adjustment as it matched their expectations. Providing thermal feedback and allowing users to rely on this feedback to achieve the temperature setpoint task is a means of aligning delayed functional and immediate inherent feedback in the modality. *Design implications:* as emphasised by Karjalainen [17], the UI should clearly indicate the progression of thermal comfort level in the environment and provide immediate thermal feedback.

Limitations & future work. It remains unclear whether the complexity and multifactorial nature of thermal perception may hinder user experience in real-world situations. Further improvement of thermal models and the calibration process can better meet user expectations and potentially address the aforementioned challenges in use. Furthermore, alternative mappings between local and global sensations (e.g., lowering the neutral reference point to 19°C) and their combined use with visual cues could modify the perception of comfort and promote more frugal energy consumption behaviours. In the current study, we only investigated single-user scenarios; multi-user scenarios with heterogeneity in thermal comfort preference, in which the thermal modality of touch can act as a mediator between users, should also be investigated in the future. In addition, we would also like to explore alternative locations and modalities (e.g., through air) for the delivery the thermal stimuli.

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