Warmth on Demand: Designing Headphones for Enhanced Thermal Comfort in Work Environments

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Figure 1: Thermoactive headphones for thermal comfort developed with low-cost materials (A), using Peltier elements and flex-printed metal plating for heat transfer (B&C), efficiently warming the user (D).

ABSTRACT

In response to the increasing demand for personalized body temperature management, our study investigates headphones as a wearable system for enhancing thermal comfort in work environments. Utilizing a mixed-methods approach, we evaluated user experiences with our developed thermoactive prototype. The results demonstrate that active heating via headphones provides more pronounced thermal effects compared to passive heating with regular headphones, particularly around the ears, but also moderately for the whole body, offering potential relief in cold office settings. However, the qualitative insights suggest that its effectiveness in supporting whole-body thermal comfort diminishes in the presence of intense cold in extremities like hands or feet. Additionally, our findings indicate a modest link between thermal comfort and productivity-related factors, including performance, workload, and frustration during work. These insights show the potential of integrating thermal comfort solutions in everyday wearable technology like headphones, leveraging their ubiquity to enhance user well-being and work efficiency.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; *Empirical studies in ubiquitous and mobile computing*.

KEYWORDS

Headphones, Thermal Comfort, Personal Comfort Systems, Earables, 3D-Printing

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1 INTRODUCTION

Amid increasingly adverse climate conditions, there's a growing need to find efficient and flexible ways to regulate body temperature, especially in workplace settings where thermal comfort is known to substantially affect productivity and well-being [18, 25, 29, 34]. However, coming up with appropriate solutions remains a challenge, especially as thermal comfort is a highly individual phenomenon, requiring tailored solutions to meet each person's specific needs [20, 29, 33]. Previous HCI research has, for example, focused on designing smarter, socially integrated indoor environment quality systems like smart thermostats [2, 24, 27] and mediator technologies to resolve interpersonal thermal conflicts in offices [6, 7, 28, 33]. Further, scholars have explored innovations like heated desks or seats in office furniture to enhance employee comfort via personal comfort systems (PCS) [12, 29]. However, with the increasing prevalence of remote work, such stationary solutions may have a limited impact [34]. To date, many people work from home, while commuting, or at changing locations, making them ideal candidates for mobile and wearable temperature control solutions, that have only been sparsely investigated [34].

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In this work, we aim to advance wearable thermal comfort support by investigating the integration of thermoactive functionality into a well-known wearable device: over-ear headphones. We chose headphones because they provide a good body area coverage for thermal actuation, and because the head is a thermally sensitive region [19, 31, 32], making it an ideal candidate for exploring both comfort and productivity effects. Also, over-ear headphones have a high user acceptance and reach a wide user base [21, 30]. Thereby, this research integrates with the earables research developments in HCI, where scholars are exploring sensing capabilities and interaction modalities in the ear's vicinity [8, 16, 17, 26, 30] and where previous knowledge on thermal sensations can be leveraged and expanded. While such research has investigated how periauricular thermal feedback can enhance media experiences [1] and deliver inconspicuous messages [19, 31], no prior research has examined the effects of headphones on thermal comfort using active thermal actuation during work. Therefore, we have developed a functional prototype to investigate the impact of active heating on individuals' perceptions in a workplace setting. Our research questions (RQ) are:

- **RQ1:** Which effects do heatable headphones have on local and whole-body thermal sensation and comfort during work?
- **RQ2:** Are there direct or indirect effects of the thermal actuation on productivity and well-being?

To answer these RQ, we designed an experiment where participants wore either regular headphones (as a passive heating condition) or our prototype with active heating in a cool office room (19°C) for 20 minutes and repeatedly provided feedback on their comfort and related experiences while working naturally. In a mixed-method approach, we also gathered qualitative insight through open-ended questioning at the end of the study to gain deeper insights into the experience with the active heating system. The following sections provide an overview of previous related HCI works, detail our system development process, and finally, report and discuss the results from the user study.

2 RELATED WORK

2.1 Intelligent Thermal Support & Personal Comfort Systems

In recent years, HCI research has increasingly highlighted how poor indoor environment quality impacts worker productivity [28], has examined the balance between user comfort and energy savings with smart thermostats, and has emphasized the complexity of shared-space thermal comfort [24]. Related studies have also highlighted the differences in thermal preferences across genders and ages [20], and have discussed individualized thermal comfort and conflict resolution in shared spaces [6, 33], for example by increasing awareness for thermal preferences in workplaces [7]. Additionally, HCI research has improved thermostat technologies by introducing machine learning-based heating adaptations [2], or more intuitive adaption based on user logs [27] to tackle thermal comfort personalization challenges.

As an alternative to central room climate systems, personal comfort system research aims to enhance individual comfort and increase energy efficiency, using technologies like thermoactive wearables [25, 34] and stationary thermal support systems like furniture [18, 29]. Wearable systems, such as the *Embr Wave* wrist device [34], offer mobility and personalization, but have only been sparsely researched, likely due to their small body surface coverage and the related challenges in affecting changes in whole-body thermal support. Our study seeks to expand this knowledge of local and global thermal effects by investigating headphones as a thermoactive wearable. This is particularly relevant as headphones are widely used and socially accepted in work environments [16, 17, 21, 26]. Also, unlike previous wearables that target peripheral body parts, headphones would provide thermal actuation directly at the head. This could significantly impact comfort and work productivity, given the brain's known sensitivity to temperature changes [32].

2.2 Whole-Body & Periauricular Thermal Perception

It should be acknowledged that a plethora of previous HCI research has covered the general concept of thermal user interaction potentials, for example by describing the subjective dimensions of thermal experience [35], how they can be mapped to emotional models [36], and addressing how thermal cues can be used for discrete notifications [37]. Such thermal notification effects have been investigated with car seats [11], clothing [4], or with smartwatch wristband straps [22], showing effective information transmission, especially when other sensory modalities are busy, but also that transmission bandwidth and speed are smaller than other modalities.

Further, the use of thermal actuation has also been explicitly studied in the periauricular region. Researchers have investigated how sensory experiences may be enhanced [1], or how thermal feedback can be used for discreet, context-aware notifications around the ears [19, 31]. Akiyama et al.'s [1] ***ThermOn*** system, designed to augment music listening experiences, used thermal stimuli applied to the ears via Peltier elements controlled by an Arduino. In their study, participants experienced music with and without ThermOn, reporting a more intense and focused listening experience with the thermal actuation. Nasser et al.'s [19] ***ThermEarhook*** device explored discreet notification methods through thermal stimulation of the auricular skin. It featured a base with up to five Peltier elements for varied stimulation patterns. Their experiments showed that users could recognize notifications with the device, preferring lower temperatures for warm stimuli. This research suggests new notification methods for environments where traditional alerts are disruptive or for individuals with hearing impairments. Lastly, Stanke et al.'s [31] ***Can You Ear Me?*** study used ear clips with integrated Peltier elements for private notifications. They evaluated users' ability to distinguish and respond to thermal patterns, finding the approach noticeable and effective for discreet notifications. Together, these findings underscore the periauricular region's sensitivity to thermal sensations, making it a promising target area for affecting thermal comfort.

3 METHOD

3.1 Prototype Design

3.1.1 First Iteration. To investigate the effects of thermal support via headphones, we adopted a rapid prototyping method, prioritizing low material costs and ease of reproduction. Our prototype's foundation is a 3D-printable, open-source headphone design[1], chosen for its simplicity and adaptability. We focused on implementing a heating function first, as it is less complex compared to cooling, which requires elaborate heat dissipation mechanisms. In our first design, we placed a Peltier element (3.9 V max operating voltage, 2.4 A max current, dimensions 10x10x2.5 mm) directly underneath the cushion cover. Temperature measurements on both the Peltier element and cushion surface were conducted, as shown in Figure 2-A. Here, a significant temperature increase on the cushion surface, over one degree, was only detectable when the Peltier element reached 53 °C at 0.3 A. Beyond this, the cushion surface temperature climbed more swiftly with each 50 mA increment. However, to avoid damage to the cushion, headphone housing, or Peltier element, the test ceased at a current of 0.4 A and a Peltier element temperature of 85 °C, recording a surface temperature of 26.6 °C on the cushion. Thus, this heat transfer method proved being ineffective.

3.1.2 Second Iteration. In our second design, we enhanced thermal transfer by placing a thin metal sheet atop the cushions, using a flexible printed circuit board (PCB) with exposed copper and gold plating (see Figure 2-B). This design routes heat parallel to the surface, particularly around the ear, and conceals the Peltier elements inside the headphones, avoiding direct user contact with hot surfaces for safety and aesthetic reasons (Figure 2-C). Small aluminum heat sinks on the headphone exterior, attached to the Peltier elements, dissipate heat from the cooler side at higher currents. This approach significantly improved thermal conductivity; the cushion surface exceeded 30 °C, while the Peltier element maintained a safer temperature of 42.5 °C at 0.35 A, a temperature that is safely below the glass transition temperature of the used PLA material and also to being touched. To enable operation of the thermal regulation headphones, an external power supply was developed (see Figure 2-E). It includes a Buck-Boost ZK-4KX voltage converter, allowing flexible output voltage adjustment and maximum current to control the Peltier element temperature. It also features a YZXStudio ZY12PDN PD-Trigger, enabling the use of standard USB-C chargers. We opted for this power supply design to realize a user study fast before moving to full technical integration into a portable device. As a final development step, we measured the thermal changes upon wearing the headphones with a thermal imaging camera (Teledyne FLIR E60). Figure 1-D shows that the skin region near the cushions is warmer after wearing the headphones for five minutes (showing a temperature increase of 1.5 °C).

3.2 Study Design

3.2.1 Procedure & Materials. To test the effects of the thermoactive headphones, we designed a user study, following the previous work by Wang et al. [34], that comprised two main phases: a 20-minute acclimatization phase and a subsequent 20-minute stimulation phase wearing the headphones (see Figure 3). The stimulation phase started with the participants putting on and adjusting the headphones to a comfortable temperature. To ensure they felt the heating effect, they watched a calming ocean scene video for five minutes [23], after which they could finalize their temperature settings. Focusing on natural work conditions, participants used their own laptops and work tasks in a controlled office environment. The only imposed limitation was that no meetings should be held and that participants should be sitting at the desk for the entire study period. Each session lasted around 50 minutes. The 19°C office setting was derived from a recent real-world case. In the winter of 2022 to 2023, the German government implemented energy savings measures that expected public institutions (like universities) to only heat office rooms to this temperature - a situation that created heated discussion among the general population and showed the need for personalized warming solutions.

3.2.2 Measures. Upon arrival, participants first signed the informed consent form. Next, participants provided demographic information (age and gender) and their perceived level of thermal comfort and sensations (separately for the ear and the whole body) adapting a questionnaire used in previous personal comfort systems research [34]. Thermal sensation reports could range from "cold" to "hot" (-20 to +20 slider, 0 = "neutral"), and thermal comfort reports range from "very uncomfortable" to "very comfortable" (-20 to +20 slider, 0 = "indifferent"). Then, after every ten minutes, the participants were alerted by a bell sound that they should fill out a questionnaire. In these instances, their perceptions of thermal comfort and work-related experiences were collected. To keep the response burden low, we chose to include the six questions from the NASA Task Load Index (TLX) [13], covering three dimensions of task demand (physical, mental, and temporal) and also perceived performance, effort, and frustration with one item each (slider scale ranging from 1-21). The TLX has also been used in related previous research to study thermal work impact [9]. At the end of the study, participants took off the headphones and reported on their experience with the headphones through closed UX questions (four questions on usability from related headphones research [16], and three questions for future use intentions [10]). Finally, to gather deeper insights, we added a set of open questions to the end of the study asking the participants to elaborate on their perceptions of ergonomics, thermal effects, further use, and design/feature requests.

3.2.3 Sample. The study was conducted once with activated (study 1) and once with deactivated heating (study 2) using the same headphones, to also test whether similar thermal effects would emerge with regular headphones (between-subject manipulation). Both data collections were completed over two days in the same office room, maintained at 19°C using air conditioning to prevent external temperature influences, with room temperature monitored by a ThermoPro TP53 thermometer. Study 1 (active heating) recorded average room temperatures of 18.56°C (SD: 0.20) at the start and 18.76°C (SD: 0.45) at the end, with an outdoor temperature average of 5.25°C (SD: 3.06). Study 2 (passive heating) had averages of 19.08°C (SD: 0.44) and 19.83°C (SD: 0.63), with an outdoor average of 8.56°C (SD: 2.12). Seven participants (three female, four male, age

[1] Homebrew Headphones - https://homebrewheadphones.com/ - last accessed 22.01.2024

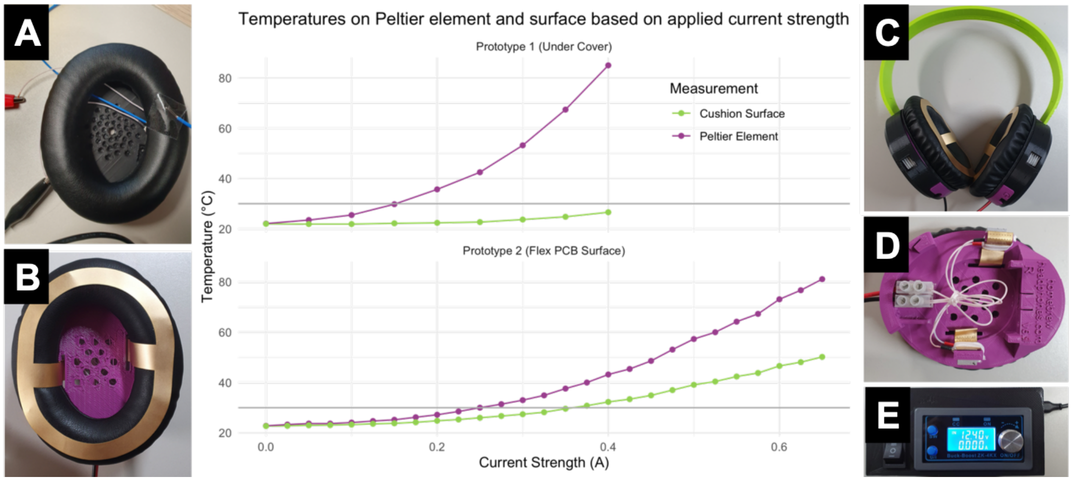

Figure 2: Design and thermal properties of two heating prototype iterations (A&B). The final system is shown on the right (C-E).

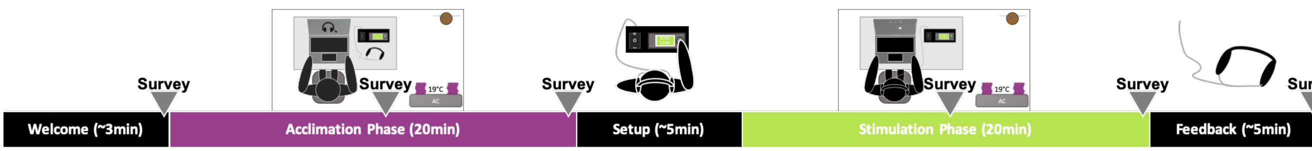

Figure 3: The study procedure showing the within-subject protocol using either the passive or active heating headphones.

range: 26-34) engaged in study 1, and another seven (two female, five male, age range: 26-31) in study 2.

4 ANALYSIS AND RESULTS

4.1 Thermal Effect Perceptions

At the start of the analysis, all report variables were mean-centered by subtracting each participant's average response to account for the inter-individual variance, as is common practice for hierarchical data [14]. For the thermal perceptions, the perceived sensation and comfort were analysed both locally (around the ears) and globally (for the whole body). The progressions of these thermal perceptions are shown in Figure 4-A. To test the effect of the treatments (heating vs. no heating and active vs. passive heating), two-way mixed ANOVAs were calculated based on linear mixed models (LMM) with the participant ID as the random intercept. For all four variables, a significant interaction effect between the study phase (acclimatization or stimulation) and the heating type (active or passive) is found (Ear Comfort: $F = 7.321, p = .0094, \eta_p^2 = 0.132$, Ear Sensation: $F = 13.742, p = .0005, \eta_p^2 = 0.223$, Whole Body Comfort: $F = 8.299, p = 0.0059, \eta_p^2 = 0.147$, Whole Body Sensation: $F = 12.313, p = .0010, \eta_p^2 = 0.204$). Follow-up comparisons of the simple effects of the study phase (within-subject factor) for the active and passive systems individually, further show that particularly for the active heating system, an increase in ear and whole-body thermal sensation and comfort can be observed during the stimulation phase that is either weaker or not present with the passive system (see these results on 4-A above the reported values). Based on the corresponding effect sizes, it can also be seen that the changes are larger around the ears than for the whole body, indicating that the thermal effects are stronger locally than globally.

Following up on these effects, we next calculated repeated-measures correlations (see [3]) to assess the relationship between these thermal variables and with work-related perceptions (performance, task demands, and frustration). The results of the correlations are shown in Figure 4-B. Large and positive correlations are found between the thermal sensations and the perceived comfort (Ear: $r = 0.56, p < .0001$; Whole Body: $r = 0.48, p < .0001$). Also, moderate-sized positive correlations are observed between thermal comfort on the ears and the whole body ($r = 0.40, p = .0007$), and the thermal sensations on the ears and the whole body ($r = 0.42, p = .0004$). The correlation between the thermal sensation around the ear and the whole-body comfort is also positive and significant, but weaker ($r = 0.29, p = .0212$). This indicates that local effects (heating around the ears) have a lower impact on the whole-body comfort. Furthermore, we find a series of small to moderate-sized, significant correlations between the comfort dimensions and the reports on perceived performance (positive), frustration (negative), and temporal and physical demand (negative). These relationships are stronger for the whole body comfort than for the ear comfort (e.g., ear comfort - performance $r = 0.28, p = .0224$; whole body comfort - performance $r = 0.43, p = .0004$), except for the frustration dimension that is similarly strong for both regions.

4.2 UX Reports & Qualitative Feedback

To better understand our participants' system use perceptions, we specifically analyzed their reports on the active system (study 1). Figure 5 shows the distribution of the participants' responses on

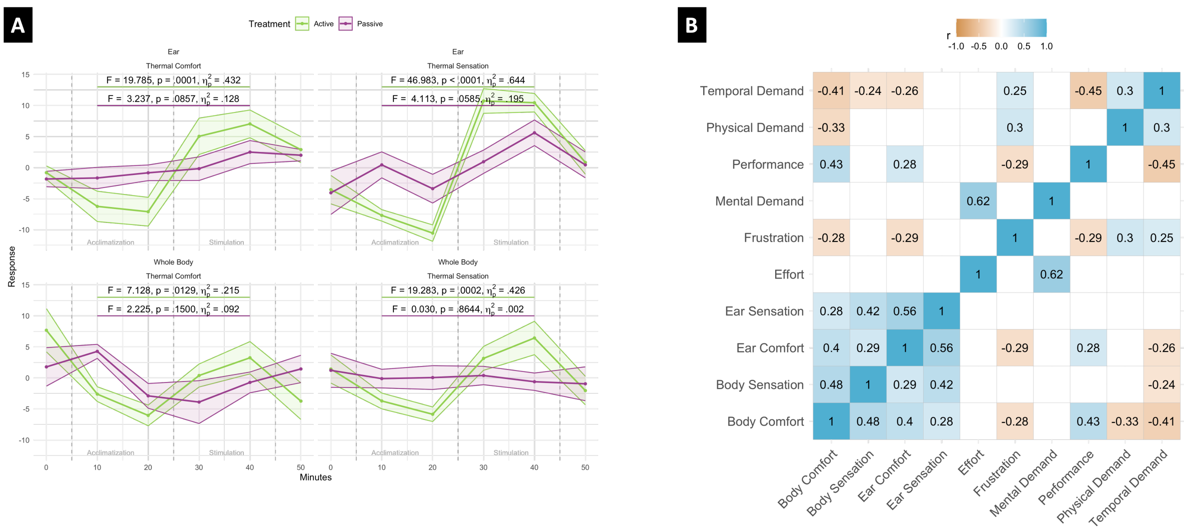

Figure 4: Self-reported perceptions of thermal sensations and comfort (A) and their correlations with work-related experiences (B). Correlations with $p > .05$ are not shown.

the closed UX questions. Overall, the participants consistently reported positive perceptions of the headphones setup's ease ($mean = 6.71, SD = 0.49$) and speed ($mean = 6.71, SD = 0.49$). Also, the participants reported relatively high interest in using the system again ($mean = 5.52, SD = 0.74$). Comfort ($mean = 5.14, SD = 1.95$) and looks ($mean = 4.29, SD = 2.14$) were rated less positively and showed substantial variation, indicating that wearability needs and preferences were not well addressed.

To further improve our understanding of these experiences, a thematic analysis [5] was conducted on the data collected in the open feedback forms at the end of the experiment. Two researchers coded all the responses independently first, and then they jointly developed a coding tree through an in-depth discussion of the observed patterns. Based on the coding tree, the following three to four themes per category were identified, comprising 15 themes in total.

In terms of ***ergonomics***, multiple participants (n=3) reported that the headphones were overall comfortable and easy to use (e.g., *"They were comfortable and did not hinder working."* – P6 / F). Beyond that, several participants (n=4) noted that the fit could be improved (e.g., *"Good, feel warm, maybe not perfect fit."* - P4 / M), that they'd like to see a better way to adjust the size of the headphones (n=3) (e.g., *"For me, they would definitely need to be adjustable in size as they were slightly too big for my head."* - P5 / F), and that the headband pressure was too high (n=2) (e.g., *"Make the "beam" over the head more flexible."* - P6 / F).

Regarding the ***thermal effects***, many users (n=6) reported a generally pleasant experience (e.g., *"It was pleasant as they insulated and warmed me at the same time."* - P3 / M). Some participants (n=3) stated that they felt that the heating had a global effect (e.g., *"I think the headphones helped me feel more heat all over my body."* - P1 / M). However, several participants (n=5) also explicitly stated that they primarily felt a local sensation (e.g., *"My ears felt warm, the rest of my body was still feeling cold."* - P7 / M). Interestingly, multiple participants (n=3) highlighted a particular limitation of the thermal effectivity through cold extremities (e.g., *"I felt like my upper body was getting warmer, but my hands stayed very cold and they usually bother me the most."* (P5 / F)).

About the ***future use***, many participants (n=6) expressed interest in using the heating function further (e.g., *"Absolutely yes, I would be curious to use it."* - P3 / M) and deliberated about use cases at work (n=4) (e.g., *"I think it could be useful when you are sitting in a cold office and have a video meeting in which you do not want to wear a hat but still feel comfortable."* - P5/ F), and in leisure settings (n=3) (e.g., *"I think it would be nice in non-office settings in winter as well, e.g. walking outside/ jogging etc. like 'ear warmers'."* - P6 / F).

For the ***design & features***, only few remarks were made. A common one (n=3) was a preference for different headphone colors (e.g., *"I'd prefer a more simple / plain design (e.g., black, white, grey, ...)."* - P8 / F). Some participants (n=2) also remarked about integrating the thermal controls directly into the headset (e.g., *"It would be really cool if you could adjust the temperature via touch on one side of the headphones, similar to the volume."* - P5 / F). Finally, participants (n=2) remarked about developing more dynamic heating functions (e.g., *"I lowered the temperature further, after about 5/10 minutes it seemed to perceive more heat."* - P2 / M).

5 DISCUSSION & OUTLOOK

5.1 Major Observations & Reflection

In our study, we explored using headphones as a thermoactive wearable for personal thermoregulation and comfort. Our mixed-method approach has led to several key observations that necessitate critical reflection. Primarily, we observed that active heating elicits a stronger effect than passive heating, showing a potential to make cold, uncomfortable office environments more bearable. Importantly, while some global (whole-body) effects were observed, the thermal effects were more pronounced locally (around the ears). It

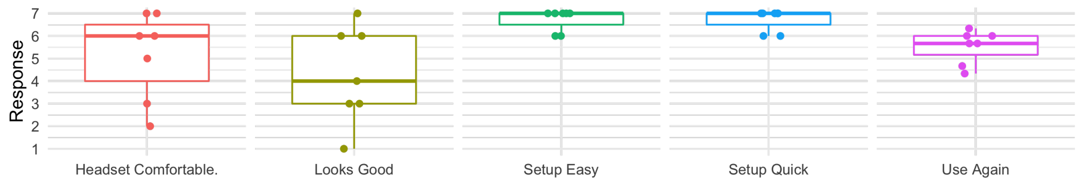

Figure 5: Responses to the closed-question UX dimensions.

appears, that the thermoactive headphones alleviate general thermal discomfort through the indirect process of feeling "something" warming around your ears. Yet, this effect appears to be countered if strong negative (cold) sensations are present simultaneously, for example in the body extremities. Therefore, thermoactive headphones might be helpful when an overall thermal discomfort is experienced, but not as much when a user primarily has icy hands. Our results also indicated a modest correlation between thermal effects and factors like performance, task demands and frustration, aligning with existing research on thermal comfort's role in productivity and well-being [9, 12, 25]. Although these effects were small, they highlight the potential significance of adding thermal stimulation through wearables in workplace settings, especially given the widespread accessibility of headphone technology. This potential is also supported by the reported interest in further device use.

5.2 Limitations & Future Work

Looking at the limitations of our research, we acknowledge the need for more comprehensive data to enhance internal validity and better understand the thermal effects and experiences. For example, the small sample size of our study limited our ability to examine gender effects that have been saliently discussed in previous work [20]. Similarly, the restricted posture (sitting for the entire session), might also have pronounced the occurrence of strong cold sensations in the extremities. We chose this setting to simulate a typical knowledge work session of focused work but future work should include a more comprehensive evaluation of various types of regular office work behaviors. Additionally, while open tasks offer external validity, they complicate the assessment task-related factors. Future studies should include controlled tasks with varied difficulty or tasks sensitive to response times to more precisely determine the impact of these thermoregulation headphones on cognitive performance. Further, including biosensors into the headphones like EEG [16] or heart rate [17] could also provide more objective insights into how attention and stress levels are affected by such a local heating system sitting close to the brain.

Future work should also focus on optimizing and extending the thermal feedback mechanisms. For example, these extensions should add thermal actuators to the headband. By enlarging the surface area involved in thermal regulation, we anticipate not only a possible intensification of the thermal effects but also an enhancement in the versatility of the application. For instance, when headphones are not worn on the ears but are instead resting around the neck, incorporating thermal elements into the headband could allow heating or cooling effects on the neck or even the upper chest area. This adaptation could significantly broaden the system's use cases, making it a more flexible solution in varying environmental conditions and user scenarios. Moreover, exploring synergistic effects arising from the concurrent use of multiple wearable PCS devices presents a fascinating avenue for research. Integrating thermoregulation in headphones with other wearable devices, such as wristbands, could potentially elevate the overall impact on whole-body thermal sensation and comfort. This combined approach might address the limitations observed in localized heating, providing a more comprehensive and effective solution for personal thermal regulation.

Also, a key objective is to develop an effective cooling mechanism. Cooling is more complex than heating due to the need for efficient heat removal and dissipation while maintaining comfort [15]. Our initial tests show that our current design inadequately achieves cooling of the flex PCB, which is simultaneously subjected to the heat from the user's skin. Achieving a cooling function would greatly extend the applicability of this system in a variety of work environment conditions. As environmental climate conditions intensify, the need for effective and efficient methods to provide thermal comfort becomes increasingly pressing. The HCI community is ideally positioned to lead in developing technologies that address technical challenges and cater to user needs. With its straightforward and reproducible design approach, we hope our research will stimulate further exploration in this area, contributing to the development of user-friendly thermal comfort solutions.

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