Heatables: Effects of Infrared-LED-Induced Ear Heating on Thermal Perception, Comfort, and Cognitive Performance

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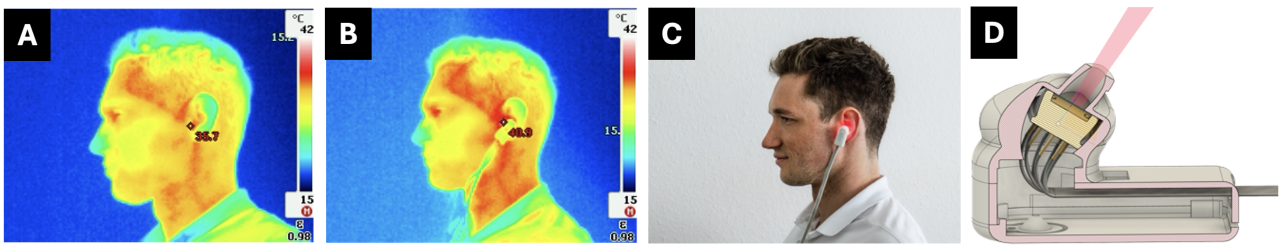

Figure 1: Visual overview of experimental conditions and prototype design, captured using a Testo 883-1 infrared thermal camera. (A) Infrared image of a participant wearing the placebo device after 45 minutes of cold exposure. (B) Infrared image of a participant wearing the active Heatables device after 45 minutes of cold exposure, highlighting localized warming around the ear region. (C) Photograph of a participant wearing the Heatables device. (D) Cross-sectional schematic of the Heatables.

Abstract

Maintaining thermal comfort in shared indoor environments remains challenging, as centralized HVAC systems are slow to adapt and standardized to group norms. Cold exposure not only reduces subjective comfort but can impair cognitive performance, particularly under moderate to severe cold stress. Personal Comfort Systems (PCS) have shown promise by providing localized heating, yet many designs target distal body parts with low thermosensitivity and often lack portability. In this work, we investigate whether targeted thermal stimulation using in-ear worn devices can manipulate thermal perception and enhance thermal comfort. We present *Heatables*, a novel in-ear wearable that emits Near-Infrared (NIR) and Infrared (IR) radiation via integrated LEDs to deliver localized optical heating. This approach leverages NIR-IR's ability to penetrate deeper tissues, offering advantages over traditional resistive heating limited to surface warming. In a placebo-controlled study with 24 participants, each exposed for 150 minutes in a cool office environment (≈ 17.5 °C) to simulate sustained cold stress during typical sedentary office activities, Heatables significantly increased the perceived ambient temperature by around 1.5 °C and delayed cold discomfort. Importantly, thermal benefits extended beyond the ear region, improving both whole-body comfort and thermal acceptability. These findings position in-ear NIR-IR-LED-based stimulation as a promising modality for unobtrusive thermal comfort enhancement in everyday contexts.

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CCS Concepts

• **Human-centered computing → Empirical studies in HCI**.

Keywords

earables; hearables; infrared stimulation; thermal stimulation; thermal perception; personal comfort systems

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1 Introduction

In shared indoor spaces, Heating, Ventilation, and Air Conditioning (HVAC) systems adapt slowly and are typically optimized for group norms, often leading to discomfort and thermal conflicts in multi-user settings [3, 12, 32]. Amid rising energy costs, many households reduce heating, relying on partially warmed spaces, conditions that heighten thermal vulnerability [33]. Cold exposure not only impairs comfort but also cognitive performance, including memory, attention, and reaction time, with some effects persisting post-rewarming [8, 14, 30]. These challenges underscore the need for energy-efficient Personal Comfort Systems (PCS) that deliver localized heating without conditioning entire rooms [24, 36]. Yet many PCS remain bulky or target thermally insensitive distal regions, limiting daily usability. Wearables like headphones and earbuds offer new opportunities for seamless thermal stimulation [26, 28]. The auditory canal is richly vascularized and located near the hypothalamus, enabling efficient heat transfer and thermoregulatory coupling [5, 22]. Combined with tissue penetration of near- and infrared (NIR/IR) radiation [10, 13], the ear becomes a promising site for perceptual thermal modulation.

We propose a new approach: delivering deep-tissue heat through in-ear wearables. *Heatables* use IR/NIR-LEDs to optically warm the auditory canal, enabling deeper, more distributed stimulation than resistive heating [10]. In a placebo-controlled study under cool office conditions (≈ 17.5 °C, 150 minutes), we tested whether (1) in-ear IR/NIR stimulation elevates subjective temperature estimates (ear, wrist, ambient), (2) improves thermal perception, acceptance, and comfort, and (3) preserves cognitive performance, assessed via the Stroop Color and Word Test.

2 Related Work

Personal Comfort Systems. Personal Comfort Systems (PCS) provide individualized localized heating or cooling tailored to individual needs, enabling improved comfort and reduced energy consumption. Examples include heated office chairs [11, 36], thermoelectric clothing [19, 24], and wearable leg heaters [34]. While effective in raising localized temperatures, many PCS target body regions such as wrists or legs that exhibit relatively low thermal sensitivity.

Thermal Stimulation via Head and Ears. Recent research in the field of human-computer interaction (HCI) has identified the head and ears as being highly thermosensitive. This is summarised in Luo et al.'s body map of thermal sensitivity.[21]. Studies have explored periauricular feedback to enhance comfort or modulate affect [2, 23, 29]. Knierim et al. [17] demonstrated that over-ear thermal stimulation via headphones can enhance both local and whole-body thermal comfort during desk work, comparing active heating (via embedded elements) to passive insulation.

However, these approaches primarily target surface warming around the ear, not the vascularized tissues deeper within the auditory canal. While the auditory canal is compact, it contains richly perfused epithelial and cartilaginous tissue and is thermally coupled to core regulation via the tympanic membrane and surrounding vasculature [5, 22]. These anatomical features make it a promising site for thermal stimulation, particularly with NIR-IR radiation that can penetrate several millimeters into soft tissue [31]. In-ear thermal stimulation thus remains largely underexplored, despite its potential to influence thermal perception through both local deep-tissue heating and anatomical proximity to thermoregulatory centers.

Optical Heating for Deep Tissue Warming. Near-Infrared (NIR) and Infrared (IR) light are well-established for their ability to penetrate biological tissues [10, 13]. Therapeutic applications of NIR-IR radiation, such as pain relief and improved circulation, highlight its potential for safe and effective thermal stimulation [31].

3 Heatables

We introduce Heatables, custom in-ear wearables delivering localized optical heat (see Figure 1). The system resembles a conventional pair of wired earphones and builds on the in-ear form factor of OpenEarable 2.0 [27]. To accommodate individual ear anatomies, maximize stability, and improve fit and comfort Heatables can be fitted with ear tips of varying sizes.

Each earpiece integrates a multichip LED (MTMD6894T38[1]) emitting at 670 nm (red), 810 nm (IR), and 950 nm (NIR). For stimulation, only the 810 nm and 950 nm channels were activated and modulated via PWM at 100 Hz (10 ms cycle, 59 % duty cycle) with a forward current of 300 mA. This yielded an average input power of 480 mW per earpiece. Given the LEDs' limited optical efficiency (28% at 810 nm, 9% at 950 nm), it should be noted that the conversion to optical power of the LEDs is inherently limited. The system is USB-powered and includes an Arduino UNO, custom PCBs, thermal safeguards, and interchangeable silicone tips for anatomical fit.

4 Evaluation

To investigate the perceptual and cognitive effects of in-ear thermal stimulation, we conducted a mixed factorial study with one between-subjects factor (stimulation condition: Heatables vs. Placebo) and one within-subjects factor (device exposure: Device vs. No Device). Participants were randomly assigned to four counterbalanced experimental groups (stimulation × device) to control for order effects and perceptual expectancy biases.

4.1 Experimental Setting

Experiments were conducted in a thermally controlled office environment maintained at approximately 17.5 °C. This ambient temperature is well below the typical operative range in European office settings, where comfort temperatures generally fall between 22.5 °C and 25 °C during occupancy [16]. Participants wore light to moderately insulating office clothing (e.g., T-shirt or pullover and jeans) and engaged in sedentary desk-based activities such as typing and reading, corresponding to a low physical exertion level of approximately 1.0–1.2 Metabolic Equivalents of Task (MET) [1, 20]. Given the low metabolic heat production, the environment represented a sub-neutral thermal context likely to induce gradual cold discomfort. Participants were seated individually at standardized workstations equipped with a laptop and external input devices. To ensure perceptually meaningful stimulation, participants in the Heatables condition underwent individualized NIR-IR intensity adjustments prior to the experimental session, accounting for known interindividual differences in thermal sensitivity [13].

4.2 Experimental Design

We employed a 2×2 mixed factorial design with one between-subjects factor (Stimulation Condition: Heatables vs. Placebo) and one within-subjects factor (Device Exposure: Device vs. No Device). To account for order effects and perceptual expectancy, exposure

[1] https://www.mouser.de/datasheet/2/1094/MTMD6894T38-2255938.pdf

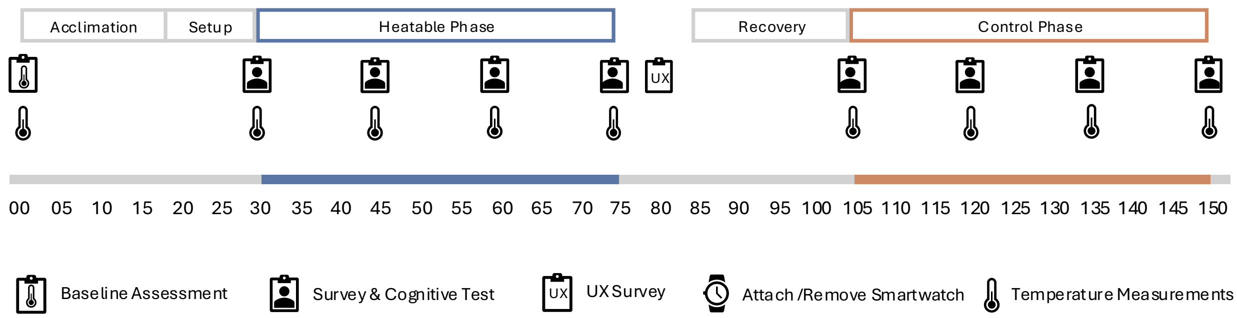

Figure 2: Study procedure illustrating the mixed factorial design. Each participant completed one stimulation session (either Heatables or Placebo) and one control session (no device), with the order of exposure counterbalanced across participants. Measurements were taken at four standardized time points (0, 15, 30, and 45 minutes) during each session.

order (Device First vs. Control First) was counterbalanced, and half the participants received a visually identical but non-thermal placebo. Participants were randomly assigned to one of four groups and completed two sessions: one with their assigned device and one control without any device. Table 1 summarizes group allocation.

Table 1: Participant allocation across counterbalanced experimental groups.

Group	Condition Order	Gender (m/f)
A	Heatables → No Device	3 / 3
B	No Device → Heatables	3 / 3
C	Placebo → No Device	5 / 1
D	No Device → Placebo	4 / 2

4.3 Study Procedure

The procedure for each participant was as follows (see Figure 2):

(1) **Baseline Phase (20 min):** Participants provided informed consent, demographic data, and thermal insulation ratings.
(2) **Setup Phase (10 min):** Participants inserted the device individually adjusted the NIR-IR intensity. All participants subsequently engaged in a passive 10-minute media viewing task to stabilize thermal conditions.
(3) **Stimulation Phase (45 min):** Participants engaged in self-directed but sedentary desk-based tasks resembling everyday work, including reading, literature searches, scientific writing, and coding. These tasks were chosen to reflect naturalistic work contexts while maintaining low physical activity. Measurements were taken at time points (T1–T4).
(4) **Recovery Phase (20 min):** A structured rest phase allowed thermal and physiological parameters to return to baseline.
(5) **Control Phase (45 min):** Participants repeated the same task protocol without wearing any device, with measurements again collected at four time points (T5–T8).

4.4 Measurements and Metrics

Objective and subjective data were collected at eight sequential timepoints (T1–T8). This consistent indexing allowed direct comparisons between exposure conditions while accounting for session timing differences.

4.4.1 Temperature Data. Physiological measurements included tympanic temperature (Braun ThermoScan 7), wrist surface temperature (Bosch UniversalTemp infrared thermometer), and ambient temperature (Testo 610 thermo-hygrometer).

4.4.2 Thermal Estimation and Subjective Perception. Cognitive performance was assessed using a computerized Stroop Color and Word Test, administered at each of the eight measurement timepoints (T1–T8). Each session was preceded by a brief training block. The test comprised 40 randomized trials per timepoint, including both congruent and incongruent conditions. Participants responded via keyboard, and each trial remained on screen until a response was made. Sessions were self-paced and typically lasted under two minutes. Across the experiment, participants completed a total of 320 Stroop trials (8 sessions × 40 trials), allowing for within-subject tracking of performance over time. From each session, we extracted response accuracy, mean reaction time (RT), and Stroop interference scores (incongruent minus congruent RT), indexing selective attention, processing speed, and cognitive control.

4.4.3 User Experience Evaluation. After completing the experimental session (with Heatables or Placebo), participants filled out a user experience (UX) questionnaire assessing device comfort, usability, perceived safety, thermal effectiveness, and future usage intentions, using 7-point Likert scales based on the standardized Comfort Rating Scale (CRS) [18]. Open-ended questions captured qualitative feedback on ergonomics, thermal sensations, and potential application contexts for future optimizations.

5 Results

We present the results of our evaluation, temperature estimations, subjective assessments, cognitive performance outcomes, and user experience feedback. The final sample consisted of $N = 24$ participants (9 female, 15 male), with a mean age of $M = 28.33$ ($SD = 5.59$).

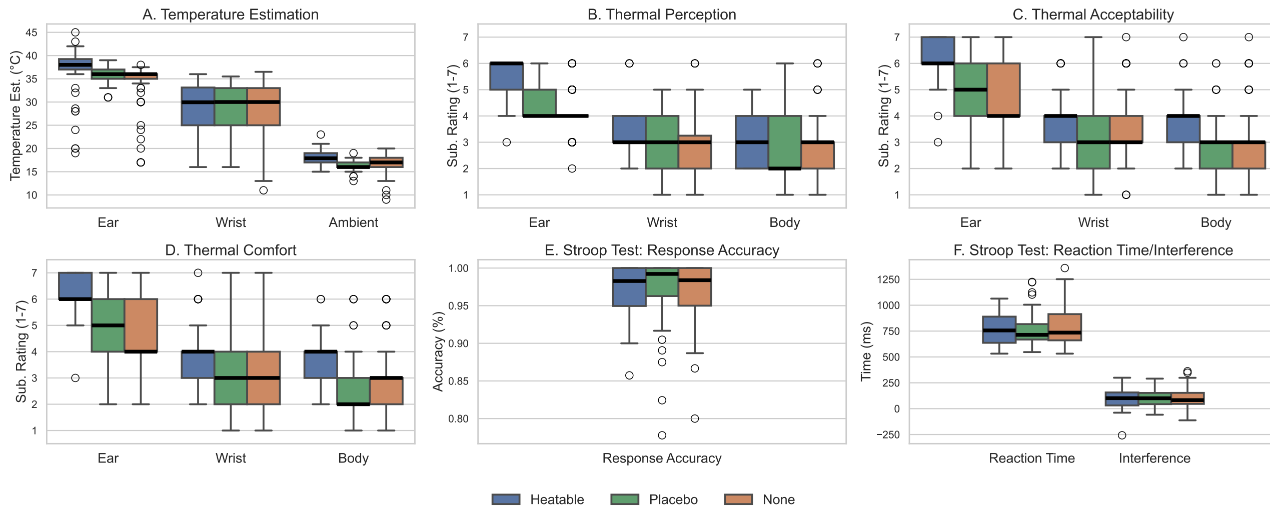

Figure 3: Box-Whisker plots of: A. temperature estimations; B.-D. subjective assessments of thermal perception, thermal acceptability, and thermal comfort; E+F. Stroop Test metrics (response accuracy and reaction time/interference). All results are presented separated for Heatable, Placebo, and control condition measurements.

To verify that ambient temperatures were consistent across experimental conditions, we compared the measured temperatures for each condition using a one-way ANOVA. No significant differences were found across conditions, $F(3, 196) = 1.16$ ($p = 0.338$), indicating comparable baseline temperatures. Similarly, preferred room temperatures did not differ significantly between groups, $F(3, 19) = 1.75$ ($p = 0.190$).

5.1 Statistical Model

For all statistical analyses but the UX reports, we employed linear mixed-effects models (LMMs). The fixed effects in each model included binary variables indicating whether the *Heatable* was active or whether a *Placebo* version was used. We furthermore included the variable *Time* to capture within-session shifts in estimation/performance. Additionally, we included the binary variable *Order*, indicating whether participants experienced the treatment (Heatable/Placebo) or control condition first. We also incorporated random intercepts for each *Participant* and random slopes for *Time* in the models. This enabled the modeling of both the heterogeneity in participants' initial responses as well as their potential variation in time-related trends.

Prior to model estimation, we evaluated the assumptions of normality of residuals and homogeneity of variance. As these assumptions were not adequately met, all model estimates and standard errors were obtained via nonparametric bootstrapping with 1,000 iterations to ensure robustness against violations of normality and heteroskedasticity assumptions.

As we have formulated directed hypotheses, we applied unidirectional testing [6, 7, 15, 25]. Since these hypotheses are exclusively formulated for the device effects, we will only report the results for *Heatable* and *Placebo* but leave out the effects of *Time* and *Order* to maintain conciseness. To account for the testing of each indicator at/for three separate locations/measures, the significance level α was adjusted to 0.017 using the Bonferroni correction.

The results from the LMMs are visualized in Figure 3 and Figure 4.

5.2 Temperature Estimation and Measurement

Temperature is always reported in Celsius. Throughout all locations, the *Heatable* led to significantly higher estimates in temperature ($b_{ear} = 3.42$, $p < 0.001$; $b_{wrist} = 1.23$, $p = 0.010$; $b_{ambient} = 1.20$, $p < 0.001$). This effect was not found in the *Placebo* condition, where the slopes were lower throughout and not statistically significant on the chosen significance level ($b_{ear} = 0.83$, $p = 0.020$; $b_{wrist} = -0.45$, $p = 0.508$; $b_{ambient} = 0.14$, $p = 0.375$).

For actual measured temperatures, significant increases were found only at the ear and wrist in the *Heatable* condition ($b_{ear} = 0.91$, $p < 0.001$; $b_{wrist} = 0.51$, $p = 0.011$; $b_{ambient} = 0.01$, $p = 0.431$). No significant changes were detected in the *Placebo* condition ($b_{ear} = -0.44$, $p = 0.404$; $b_{wrist} = -0.51$, $p = 0.130$; $b_{ambient} = 0.05$, $p = 0.212$). Notably, the observed significant effects on measured temperatures were substantially smaller in magnitude than those for perceived temperature.

5.3 Subjective Assessments

In the following, we report the results for the three measures taken in the survey. All assessments were given on a 7-point Likert scale.

5.3.1 Thermal Perception. The perception of temperature was significantly higher for all locations when the *Heatable* was worn ($b_{ear} = 1.97$, $p < 0.001$; $b_{wrist} = 0.66$, $p = 0.013$; $b_{body} = 0.71$, $p = 0.007$). For the *Placebo*, this effect was only observed for perception of ear temperature ($b_{ear} = 0.43$, $p = 0.015$; $b_{wrist} = 0.13$, $p = 0.280$; $b_{body} = 0.41$, $p = 0.049$).

5.3.2 Thermal Acceptance. The acceptance of temperature was significantly higher for both the ear and the body when the *Heatable*

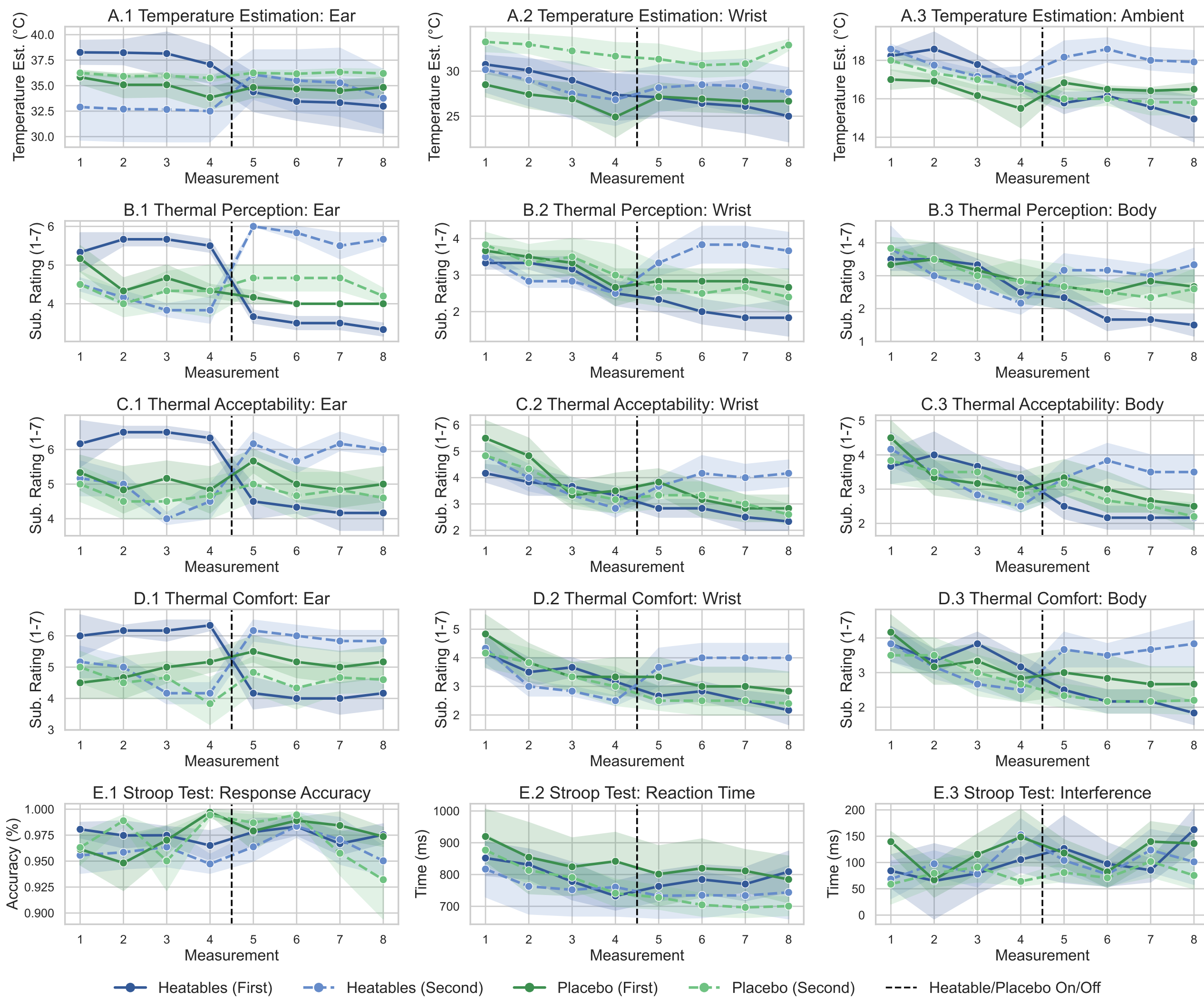

Figure 4: Temporal progression of: A. temperature estimations; subjective assessements of B. temperature perception, C. temperature acceptability, and D. temperature comfort; E. Stroop Test metrics. Results are presented across eight timepoints, separated by device (Heatables, Placebo) and exposure order. The shaded areas indicate 68% confidence intervals. The dashed line marks the point of device attachment or removal.

was worn, but not for the wrist ($b_{ear} = 1.78$, $p < 0.001$; $b_{wrist} = 0.68$, $p = 0.019$; $b_{body} = 1.04$, $p < 0.001$). Again, the *Placebo* only had this effect for the assessment at the ear ($b_{ear} = 0.58$, $p = 0.006$; $b_{wrist} = 0.45$, $p = 0.032$; $b_{body} = 0.31$, $p = 0.130$).

5.3.3 Thermal Comfort. The reported comfort was significantly higher for all locations when the *Heatable* was attached ($b_{ear} = 1.95$, $p < 0.001$; $b_{wrist} = 0.83$, $p = 0.016$; $b_{body} = 0.99$, $p < 0.001$). For the *Placebo*, the effect on comfort was only observed at the ear ($b_{ear} = 0.42$, $p = 0.006$; $b_{wrist} = -0.01$, $p = 0.967$; $b_{body} = 0.07$, $p = 0.404$).

5.4 Cognitive Performance

The Stroop test performances were reported in percentages for response accuracy and in milliseconds for reaction time and interference. Statistically significant effects were neither found for the *Heatable* ($b_{acc} = 0.007$, $p = 0.450$; $b_{react} = -15.52$, $p = 0.218$; $b_{interf} = -12.63$, $p = 0.226$) nor the *Placebo* ($b_{acc} = -0.0040$, $p = 0.618$; $b_{react} = -11.25$, $p = 0.159$; $b_{interf} = -2.09$, $p = 0.437$) throughout all measured performance indicators.

5.5 UX Reports

To assess how participants experienced wearing the Heatables in our experimental setting, we gathered both quantitative and qualitative feedback.

5.5.1 *Quantitative Reports.*

Participants generally rated the device as both comfortable (M = 6.25, SD = 0.62) and safe to use (M = 6.50, SD = 0.67), with even the lowest ratings remaining on the more favorable end of the scale. Many users reported perceiving a noticeable difference compared to regular earbuds (M = 4.67, SD = 1.72); however, this did not translate into discomfort or pain (M = 1.25, SD = 0.45). While nearly all participants indicated a willingness to use the device in private settings (M = 5.92, SD = 1.51), responses were more reserved regarding its use in public (M = 5.33, SD = 1.56). A significant difference in the placebo group emerged only for comfort ratings, with the treatment group reporting notably greater values (M_{Pl} = 5.00; t = 2.50, p = .027).

5.5.2 *Qualitative Reports.*

Participants provided open-ended feedback reflecting their subjective experience with the device. Responses were clustered into three primary themes: comfort and sensation, perceived use cases, and physical discomfort.

Thermal Comfort and Sensory Experience. Overall, the device was described as "comfortable to wear," "warm and cozy," and "relaxing." Several users noted that the warming sensation extended beyond the ears to the surrounding head region, suggesting a broader thermal perception than expected. One participant remarked, "the warmth felt like the ambient temperature became warmer slightly."

Perceived Use Cases. Many participants described potential future use of the device in cold environments, such as during winter walks, cycling, or visits to outdoor markets (e.g., "bike riding in winter," "Christmas markets," or "under a hat during a cold winter day"). Others mentioned relaxation-oriented contexts including "studying," "meditation," or "illness recovery," indicating interest in the device's warming functionality beyond physical comfort alone.

Discomfort and Adaptation. Reports of discomfort were minimal. One participant described a slight sensitivity in one ear due to the device's bulk, while another noted that "the warmth builds up and eventually makes you want to ventilate the ears." Some described the sensation as unfamiliar but not painful: "You have to get used to it, but it's not painful."

Responses were inductively clustered by the first author based on semantic similarity. The qualitative feedback aligned with the quantitative results: participants found the device comfortable and suitable for cold-weather use, with only minor concerns about heat buildup or form factor.

6 Discussion

Heatables significantly enhanced subjective thermal experience: participants reported higher *perceived* temperatures and improved thermal comfort and acceptability, despite the absence of any significant change in external environmental temperature, indicating that even slight localized heating of a small body region can influence whole-body thermal perception. These effects extended beyond the ear to the wrist and body, despite stimulation being confined to the auditory canal. This is an effect that is backed up by previous literature [35] and supports the hypothesis that the ear can act as a perceptual gateway with systemic thermal influence. Interestingly, perceived ear temperature was also minimal elevated in the placebo condition, although no measurable heat transfer occurred. This may be due to passive occlusion effects, as in-ear devices reduce airflow in the auditory canal and can lead to a mild sense of retained warmth. However, the perceptual magnitude was substantially smaller than under active stimulation, both subjectively and in measured data. Cognitive performance remained stable: Stroop accuracy was consistently high across all conditions, in line with prior work suggesting that mild cold exposure in low-demand contexts does not reliably impair cognition. Participants rated the device as safe, comfortable, and unobtrusive. Most expressed willingness to use it in private or relaxation-oriented contexts (e.g., studying, recovery). Some reported mild heat buildup , but no serious discomfort. Several associated the warmth with calming effects.

Limitations. The Stroop test may have been insensitive to subtle thermal effects, with a possible ceiling effect from consistently high accuracy. Conducting the study at a single indoor temperature (17.5 °C) limits generalizability. Individual IR intensity adjustments, while improving perceptual relevance, may have reduced participant blinding. Clothing insulation was self-reported on a five-point scale rather than measured in standardized units, limiting comparability with thermal comfort models. Long-term effects and safety were not assessed, although prior work suggests head-level IR exposure (<500 mW/cm²) is generally safe [4].

Design Implications and Future Work. Heatables demonstrate the potential of thermal feedback as a novel hearable modality. Public acceptance may improve with further miniaturization and ergonomic refinement. Integration with environmental or physiological sensing could enable adaptive in-ear heating for personalized comfort, distraction reduction, or mood regulation. To address current limitations, future studies should separate radiative from conductive heat (e.g., via IR-blocking controls), assess long-term safety, evaluate perceptual thresholds such as just-noticeable differences (1°C [9]), and use standardized clothing insulation units for better comparability with thermal comfort models.

7 Conclusion

We presented *Heatables*, an in-ear wearable delivering targeted thermal stimulation using IR-NIR-LEDs. In a placebo-controlled study under cool stress (≈ 17.5 °C), Heatables increased subjective ambient and wrist temperature estimates by about 1.2 °C (95% CI [0.7, 1.7]) and 1.2 °C (95% CI [0.3, 2.1]), respectively, compared to placebo and control. These effects suggest localized in-ear heating can induce a broader perceptual shift beyond the stimulation site. Participants also reported delayed onset of cold discomfort, while cognitive performance, assessed via Stroop tasks, remained unaffected. These findings highlight the auditory canal as a promising interface for unobtrusive, perceptually effective thermal stimulation and point to new pathways for portable personal comfort solutions in stationary and mobile contexts.

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