# ThermoFeet: Assessing On-Foot Thermal Stimuli for Directional Cues

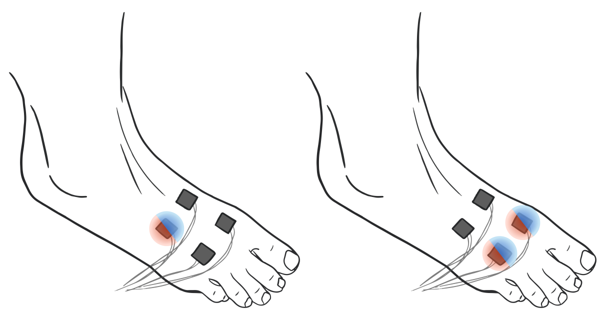

Bettina Eska
bettina.eska@ifi.lmu.de
Ludwig-Maximilians-University of Munich
Munich, Germany

Jeff-Owens Iyalekhue
j.oiyalekhue@gmail.com
Ludwig-Maximilians-University of Munich
Munich, Germany

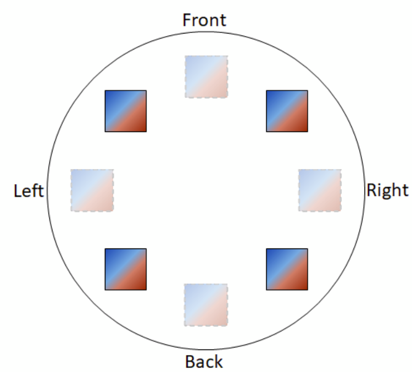
Sebastian Günther
guenther@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

Jasmin Niess
jasminni@uio.no
University of Oslo
Oslo, Norway

Florian Müller
florian.mueller@um.ifi.lmu.de
Ludwig-Maximilians-University of Munich
Munich, Germany

**(a)** ***ThermoFeet*** **attached to the foot. With one or two Peltier elements activated with either a WARM or COOL stimulus.**




**(b) Thermal stimuli ON ACTUATOR in solid color and opaque for NOT ON ACTUATOR**


## ABSTRACT

Thermal feedback has been studied for navigation purposes with directional cues and a variety of other use cases. Yet, to date, systems providing thermal feedback were primarily designed for the upper body, targeting hands and arms in particular. As these parts are often occupied with other tasks, there is a need to extend the design space of thermal feedback to other body parts. To close this gap, we assess thermal feedback on the user's feet. This research explores if creating stimuli representing any direction on a circle with only four actuators is possible. To evaluate this concept, we conducted a user study asking the participants to indicate the perceived direction after getting a hot or cold stimulus by direct actuation using one actuator or phantom actuation using two actuators. The results indicate that the detection accuracy was higher for cold signals. In addition, the results showed higher recognition for stimuli linked to actuator distribution than phantom sensation due to spatial summation.





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## CCS CONCEPTS

• **Human-centered computing**;

## KEYWORDS

thermal feedback; direction; foot; foot-based interaction

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## 1 INTRODUCTION

Current Human-Computer Interaction (HCI) research has leveraged thermal haptic feedback as a promising modality to encode and convey subtle information, such as notifications [15, 23, 26], ambient information [13, 20, 25, 32], immersiveness of virtual environments [2, 8, 24, 28]. In particular, research proposed thermal feedback as a useful modality for navigation guidance and to convey directional information [3, 15, 21, 23, 30].

However, most thermal feedback research focused on the upper body, with the hand, arms, and fingers as a primary application area [12]. While these body parts are highly sensitive for thermal stimuli [6, 14], thermal actuators on the upper body might limit the users' mobility, and, when applied to the hands or arms, orientation and rotation vary relative to the body, making it difficult to convey accurate directional information.These limitations are particularly hindering for the navigation context. As another possible solution for this context, research explored haptic feedback on the foot for different interactions [5, 17, 18, 29], and navigation tasks [16, 27, 31]. However, the proposed haptic modalities, such as vibration, are sensitive to environmental influences and might be missed due to excessive movements. Currently, the combination of thermal feedback on the feet remains underexplored, despite evidence from physiological research demonstrating the effective detection capabilities of temperature changes on the feet [6, 14].

In this paper, we propose a concept to deliver navigation cues though thermal feedback on the feet.

To simulate directions, we utilize four thermoelectric modules to render both, warm and cold temperature stimuli and attached them to the back of the foot (Figure 1a), considering the foot's thermal sensitivity heat maps and placing them on the more sensitive parts[6]. Apart from the thermal sensitivity we decided to place the actuators on the back of the foot instead of the sole to avoid creating additional sensory distractions due to the pressure exerted on the sole by the form factors of the actuator. We chose four actuators as a minimum requirement to create the four cardinal directions front, left, back, right. We added a finer granularity through the phantom sensations for a stimulus in-between by turning on two adjacent actuators. We switched on up to two actuators either with a WARM or a COOL signal. This work builds on the approach of creating phantom sensations of a sensation between the actual actuators as applied by Oohara et al. [22] and by Hong et al. [11] with vibrotactile actuators. Our aim is to determine whether individuals can *effectively understand the distinction* between these two types of actuation and *accurately identify the perceived direction.*

In this paper, we investigated the foot as an alternative body part for the application of thermal feedback. In particular, we conducted a user study (N=24) to evaluate the efficacy of perceiving varying thermal cues on the dorsal surface of the foot, where we compared identification time, error, and certainty for both, WARM and COOL, temperatures. Further, we examined the participants' ability to accurately associate individual thermal stimuli with eight specific directional cues, generated through a radial distribution of four thermoelectric Peltier elements. Thereby, we compared the effects of perceiving thermal stimuli directly at the spatial location of an actuator versus the generation of phantom sensations between two adjacent actuators [22], also known from vibrotactile research [1].

Our findings show the potential for applying thermal feedback on the foot. In particular, our results indicate a more distinct perception especially of colder stimuli for directional cues and a significantly better recognition rate for stimuli that are directly associated with the spatial distribution of the actuators compared to phantom sensation due to spatial summation.

## 2 USER STUDY

We conducted a within-subject user study in a laboratory setting. We aimed to study whether users can effectively distinguish the two actuation types and identify the ACTUATION DIRECTION. This study has been approved by the institutional ethics review board [removed for review].

### 2.1 Apparatus

For *ThermoFeet*, we used four Peltier elements (CP70137[1]) with a size of 15 x 15 x 3.8 mm. Peltier elements are thermoelectric modules that can create warm and cold stimuli by changing the polarity. We controlled the polarity by adding an eight-channel relay interface (two relays per Peltier element). We used a laboratory power supply as power source for the Peltier elements (max. $4.2V$, $4.5A$). We activated the Peltier elements programmatically and controlled the temperature through the current and the actuation duration. The temperature range for this study lay at 28°C for COOL and 36°C for WARM stimuli. Both temperatures were considerably out of any temperature pain threshold, which typically ranges from 15° C as the lower and 44° C as the upper boundary [9, 10]. To ensure participant safety, individual stimuli lasted a maximum of 20 seconds with a rate of change of approximately 2°C per second to prevent overheating. As a safety precaution, we plugged the laboratory power supply into a multi-socket with an integrated on/off switch. Although, there was no expected harm from a technical standpoint, the switch allowed users to quickly deactivate the actuator if needed. To indicate the perceived direction, the participants received a smartphone showing the possible directions on a circle (see Figure 1b). Additionally to the ACTUATION DIRECTION, we asked the user to indicate the certainty of the guess on a 5-point Likert scale.

*Actuation Method.* In the context of our study, there are eight possible ACTUATION DIRECTIONS to communicate the thermal feedback (see Figure 1b). A thermal signal is one of eight directions on a circle (RIGHT, FRONT-RIGHT, FRONT, FRONT-LEFT, LEFT, BACK-LEFT, BACK, BACK-RIGHT) starting with 0° at 3 o'clock and ascending with 45° increments counterclockwise. The directions FRONT-RIGHT, FRONT-LEFT, BACK-LEFT, BACK-RIGHT lie directly on the position of a thermal module (ON ACTUATOR). Whereas the directions RIGHT, FRONT, LEFT, BACK are NOT ON ACTUATOR. We use the interpolation of two adjacent Peltier elements simultaneously to induce the feeling of a thermal stimulus NOT ON ACTUATOR. Due to thermal referral, we can create this phantom sensation because people perceive two neighboring stimuli as one big stimulus [7].

### 2.2 Task and Study Design

The participants attached the components of the prototype described in 2.1 with medical tape on the back of their left foot (see Figure 2). We gave the participant the task to localize feedback delivered to varying positions on a circle on their feet and report the ACTUATION DIRECTION.

*2.2.1 Independent variables.* To assess the perceived directions indicated through the actuators, we varied two independent variables.

[1] https://www.cuidevices.com/product/resource/cp70.pdf

**Temperature:** As the temperature perception for warm and cold objects varies across the body, the system provides either a COOL or a WARM signal for each of the trials (two levels).

**Actuation method:** *ThermoFeet* consists of four actuators on the back of the left foot. However, we want to convey eight levels (RIGHT, FRONT-RIGHT, FRONT, FRONT-LEFT, LEFT, BACK-LEFT, BACK, BACK-RIGHT) on a circle. Therefore we varied the ACTUATION POSITION by activating only one or two adjacent actuators as the second independent variable. More precisely, the stimulus lies directly ON ACTUATOR or NOT ON ACTUATOR (eight levels).

We employed a within-subject study design. The participants repeated the task with four times per actuation method and four times per temperature. This yielded to a total of 64 trials per participant. We counterbalanced the order of conditions using a balanced Latin Square.

*2.2.2 Dependent variables.* For each trial, we logged the following dependent variables:

**Identification time** refers to the time elapsed from the beginning of the actuation until the detection and interpretation of the signal and the participant's initiation of input in response. However, participants were instructed not to respond as quickly as possible but when they felt certain about their guess.

**Error** is measured as the deviation between the direction indicated by the participants and the actual direction of actuation, providing a measure of accuracy. Since both the actuation and the reporting of the participants followed fixed steps of 45°, we normalized these values to numbers of errors. An error of 1, therefore, corresponds to a deviation of 45° degrees clockwise or counterclockwise.

**Certainty** represents the subjective assessment of participants. They were asked to rate their certainty in assessing the actuated direction on a 5-point Likert scale for each decision.

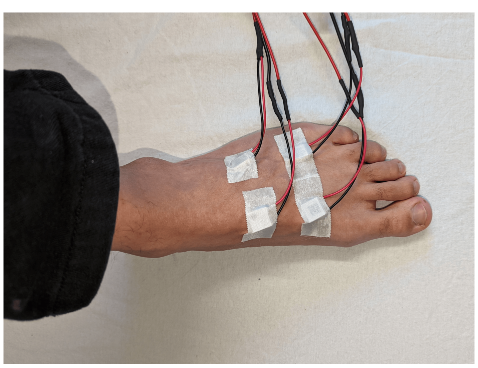


**Figure 2: *ThermoFeet* attached to the participant's left foot in the study**

## 2.3 Procedure

Our study consisted of four phases: introduction and preparation, demonstration, prototype testing, and questionnaires. After providing participants with a study overview and procedure, we started with the setup of the prototype. During the study, the participants sat on a chair and placed their left foot on cardboard on the floor in front of them to avoid temperature distraction from the floor.

Before the demonstration, participants were informed that if they find a temperature uncomfortable or painful, they can turn off the switch of the power supply and remove the actuators at any time. Then the experimenter instructed the participants how to attach the Peltier elements with the medical tape to the back of their left foot using foot landmarks for reference and following the thermal sensitivity heat map of the foot by Filingeri et al. [6]. The experimenter told the participant that the prototype induces COOL and WARM stimuli. After ensuring the correct position of the actuators, we gave the participants a demonstration of the COOL and WARM signals by sequentially actuating all possible ACTUATION DIRECTIONS on a counterclockwise circle for 7 seconds each. We started with the WARM signals followed by the COOL ones after a 30-second break. During the demonstration, the participants could already familiarize themselves with the user interface and the input method on the smartphone. The participant was then asked to state the ACTUATION DIRECTION and their level of certainty in their guess.

For the testing phase of *ThermoFeet*, the participants received noise-canceling headphones to compensate for acoustic influences, e.g., from the electric circuit. The succession of the trials ran automatically. The smartphone prompted the user with the question, "Where does the signal lead you?" to indicate the perceived direction (see Figure 1b). The actuation stopped as soon as the participants started to answer by touching the smartphone screen. We highlighted in the introduction that they should not answer as fast as possible but with high certainty. We saved the answered direction to determine the correctness of the guess later. Next, the participants had to state how certain they were with their guess. We added a 10-second break to allow the Peltier elements and the participants' skin to readjust.

## 2.4 Participants

We recruited 24 participants through university mailing lists and word of mouth. We used the data of 21 (15 identified as female, 5 identified as male, 1 preferred not to say) aged between 19 and 31 ($M = 23.7, SD = 3.9$). Three participants had to be excluded due to technical issues. Participants were compensated $10 per hour.

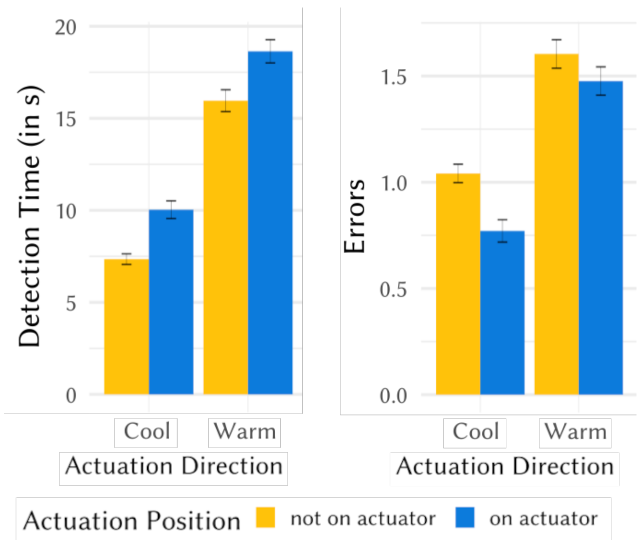
# 3 RESULTS

In the following, we report our results structured according to the dependent variables described in Section 2.

## 3.1 Identification Time

To assess the efficiency of the actuation, we measured the identification time needed to understand the cue between the beginning of the actuation and first input of a participant's response. We used Shapiro-Wilk's test to identify a violation of normality and addressed this by log-transforming the data, allowing for a parametric analysis using a 2-way RM ANOVA.

Our analysis found a significant ($F_{1,20} = 115.27$, $p < .001$) effect of ACTUATION DIRECTION with a large ($\eta^2_G = .403$) effect size. Post-hoc tests confirmed significantly shorter identification times for COOL ($M = 8.7$ s, $SD = 7.4$ s) compared to WARM ($M = 17.3$ s, $SD = 11.3$ s , $p < .001$). Our analysis also found a significant ($F_{1,20} = 43.53$, $p < .001$) main effect of ACTUATION POSITION with a small ($\eta^2_G = .040$) effect size. Post-hoc tests revealed significantly shorter identification times for NOT ON ACTUATOR ($M = 11.7$ s, $SD = 9.5$ s) compared to ON ACTUATOR ($M = 14.3$ s, $SD = 11.2$ s, $p < .001$). The analysis did not indicate interaction effects between the factors ($F_{1,20} = 1.90$, $p > .05$). The identification times are detailed in Figure 3a.




**(a) Identification Time (sec)** **(b) Errors**

**Figure 3: a) Identification time and b) Errors measured in the controlled experiment. The error is normalized to the number of 45° steps as described in Section 2.2.2. All error bars depict the standard error.**

## 3.2 Error

As a measure of accuracy, we calculated the deviation between the direction indicated by the participants and the actual direction of actuation as error. We found mean errors ranging from .72 (310°, COOL) to 1.98 (270°, WARM), see Table 1. For the analysis of the error, we fitted a Poisson regression model and applied Type III Wald chi-square tests for significance testing.

Our analysis indicated a significant ($\chi^2(1) = 39.673$, $p < .001$) main effect of the ACTUATION DIRECTION. Post-hoc tests confirmed significantly lower numbers of errors for COOL ($M = 0.9$, $SD = 0.9$) compared to WARM ($M = 1.5$, $SD = 1.2$). Our analysis also found a significant ($\chi^2(1) = 13.533$, $p < .001$) main effect of the ACTUATION POSITION. Post-hoc tests indicated significantly lower numbers of errors for ON ACTUATOR ($M = 1.1$, $SD = 1.2$) compared to NOT ON ACTUATOR ($M = 1.3$, $SD = 1.1$).

Further, significant ($\chi^2(1) = 4.499$, $p < .05$) interaction effects between both factors were revealed. While we could not find a difference in the numbers of errors between ON ACTUATOR and NOT ON ACTUATOR for WARM ($p > .05$), we found significantly lower numbers of errors for ON ACTUATOR for the COOL conditions ($p < .01$). The errors are further depicted in Figure 3.

**Table 1: The mean error values as measured in the experiment. The actuation target indicates the target position in degrees of a circle, starting at 3 o'clock and moving counter-clockwise.**

| actuation target (in °) | actuation direction | error |
|---:|---|---:|
| 0 | DirectionCold | 0.96 |
| 0 | DirectionHot | 1.44 |
| 45 | DirectionCold | 0.74 |
| 45 | DirectionHot | 1.50 |
| 90 | DirectionCold | 1.00 |
| 90 | DirectionHot | 1.57 |
| 135 | DirectionCold | 0.74 |
| 135 | DirectionHot | 1.29 |
| actuation target (in °) | actuation direction | error |
| 180 | DirectionCold | 0.85 |
| 180 | DirectionHot | 1.43 |
| 225 | DirectionCold | 0.88 |
| 225 | DirectionHot | 1.44 |
| 270 | DirectionCold | 1.36 |
| 270 | DirectionHot | 1.98 |
| 315 | DirectionCold | 0.73 |
| 315 | DirectionHot | 1.68 |

## 3.3 Certainty

To assess the participants' certainty in assessing the actuated direction, we asked them to rate each of their decisions on a 5-point

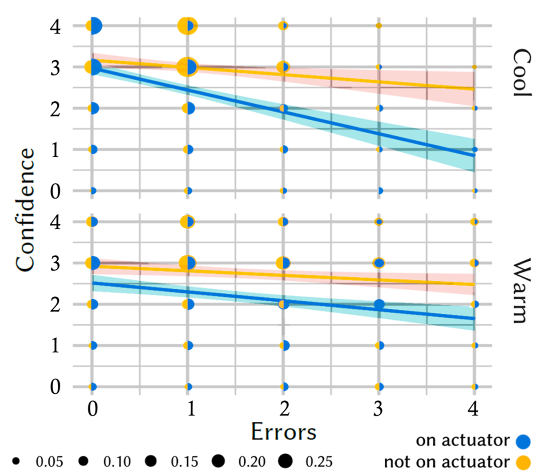



**Figure 4: Correlation of errors and certainty, grouped by ACTUATION DIRECTION and ACTUATION POSITION. The lines represent an estimate in a linear approximation.**

Likert scale. We performed a non-parametric Aligned Rank Transform (ART) analysis as proposed by Wobbrock et al. [33] and used ART-C post-hoc tests as proposed by Elkin et al. [4].

The analysis indicated a significant ($F_{1,20} = 7.05$, $p < .05$) main effect of the ACTUATION DIRECTION with a large ($\eta^2_G = .261$) effect size. Post-hoc tests revealed significantly higher certainty ratings for COOL compared to WARM, $p < .05$. The analysis also indicated a significant ($F_{1,20} = 60.39$, $p < .001$) main effect of the ACTUATION POSITION with a large ($\eta^2_G = .751$) effect size. Post-hoc tests confirmed significantly higher certainty ratings of NOT ON ACTUATOR compared to ON ACTUATOR.

Further, significant ($F_{1,20} = 5.44$, $p < .05$) interaction effects between both factors were indicated with a large ($\eta^2_G = .214$) effect size. However, post-hoc tests did not reveal any significance.

### 3.4 Correlation of Error and Certainty

To understand the connection between the accuracy and the certainty in selecting the corresponding directions, we correlated the errors and certainty ratings (see Figure 4). We calculated Kendall's $\tau$ for correlation analysis on ranks and performed the analysis per group of ACTUATION DIRECTION × ACTUATION POSITION.

Our analysis found significant negative correlations for all groups except COOL/NOT ON ACTUATOR ($r_\tau = -.07, p > .05$). In ascending order of $|\tau|$, we found the following significant correlations for the groups: WARM/NOT ON ACTUATOR ($r_\tau = -.09, p < .05$), WARM/ON ACTUATOR ($r_\tau = -.18, p < .001$), COOL/ON ACTUATOR ($r_\tau = -.35, p < .001$). This indicates that for all groups, higher certainty is correlated with lower error. This finding is more pronounced for ON ACTUATOR.

## 4 DISCUSSION

Our results show the effectiveness of thermal feedback applied to the feet to convey directional cues with four thermal actuators. We observed that COOL stimuli were significantly more effective than WARM in terms of detection speed, error rates, and participant certainty. This is in line with physiological research indicating a higher sensitivity for cold stimuli than warm ones [6].

Further, we noticed a significant effect on the ACTUATION DIRECTION with lower error when the stimulus was directly associated with the actuator's spatial location. This shows that the interpolation between two actuators and thus indicating a direction through a phantom sensation [22], may not be as intelligible as receiving feedback directly ON ACTUATOR.

Our study demonstrates that we can effectively indicate eight different directions through thermal feedback with only four actuators. However, feedback directly ON ACTUATOR resulted in fewer errors, making it a preferable choice for tasks requiring more precise and accurate feedback. However, in assessing the actuated direction, the participants detected the signal faster and reported a higher certainty value for stimuli NOT ON ACTUATOR than for ON ACTUATOR. This might be due to the fact that two adjacent actuators were active, and because of the spatial summation the stimulation was stronger with a larger area of effect, so that the participants felt more confident with their answers. For future prototypes, we would have to reduce the intensity of the interpolated stimuli to match the stimulation of one actuator better. By activating two adjacent actuators with different intensities, we could probably generate a phantom sensation that is not only limited to 45° increment steps but all steps in between.

We further observed a significant interaction effect between the temperature and the actuation method, indicating that the combination of these factors influenced the effectiveness of the thermal feedback system. We can optimize the system's efficacy with the proper selection of the temperature (WARM or COOL) combined with the actuation method. Optimizations can include more distinct gradations, for example, instead of only the two extremes of WARM and COOL. As our results indicate, COOL and NOT ON ACTUATOR outperformed their counterparts making the combination of them the first choice for more urgent notification.

The advantages of COOL over WARM stimuli, the influence of the ACTUATION DIRECTION and the interaction effects of temperature and actuation method provide insights for optimizing thermal feedback in various applications including but not limited to navigation, virtual reality, and situations requiring directional guidance. As the current version of *ThermoFeet* serves as an experimental setup, we envision that future versions can be smaller, equipped with a battery as power supply and, for example, directly integrated into a shoe, making *ThermoFeet* applicable for real-world scenarios beyond the lab. For example, with a smaller device in the shoe, it can navigate the user or add immersion to e.g. VR games. Beyond that, it remains open to study different thermal feedback patterns on the foot by adding a temporal component and activating the modules successively [23].

## 5 CONCLUSION

In this paper, we explored the application of thermal feedback to the user's feet by introducing *ThermoFeet*. Our findings indicate that detection accuracy was higher for cold signals, and stimuli associated with actuator distribution were recognized more readily than phantom sensations resulting from spatial summation. These results suggest the potential for incorporating thermal feedback on the feet as a viable option for enhancing interactive experiences. In conjunction with mobile input modalities [19], thermal feedback at the foot can thus act as a central building block for truly mobile interaction. By extending the design space of thermal feedback beyond the upper body, we further envision a future where thermal feedback systems can cater to a wider range of body parts, enabling users to receive informative and intuitive feedback in various contexts.

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