Heat-Nav: Using Temperature Changes as Navigational Cues

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ABSTRACT
HCI is increasingly exploring how temperature can be used as an interaction modality. One challenge is that temperature changes are perceived over the course of seconds. This can be attributed to both the slow response time of skin thermoreceptors and the latency of the technology used to heat and cool the skin. For this reason, thermal cues are typically used to communicate single states, such as an emotion, and then there is a pause of tens of seconds to allow the skin to re-adapt to a neutral temperature before sending another signal. In contrast, this paper presents the first experimental demonstration that continuous temperature changes can guide behaviour: significantly improving performance in a 2D maze navigation task, without having to return to a neutral state before a new signal is sent. We discuss how continuous thermal feedback may be used for real world navigational tasks.

Author Keywords
Thermal feedback; thermal haptics; navigation

ACM Classification Keywords
H.5.2. User Interfaces – Haptic IO.

INTRODUCTION
HCI research has primarily investigated whether or not thermal cues can communicate single states, for example, an emotion, activity level or social distance [4][15][9]. In these studies, the temperature is usually reset back to neutral for tens of seconds before sending a new thermal cue, a process referred to commonly as 're-adaptation'. This is necessary as the skin slowly habituates to temperature, which can undermine how strongly the participant can detect a new stimulus. There is an open question about the usefulness of thermal feedback for guiding behaviour if it is necessary to pause for tens of seconds before a new thermal cue is presented.

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The limitations of human physiology and technology present other challenges for using thermal cues to guide behaviour. The cutaneous sense of temperature is carried on nerve endings that have slow response times [6]. Non-linear interactions between these neurons result in sensory illusions such as 'synthetic heat', as illustrated by placing a hand on interlaced warm and cool bars, which results in a burning sensation [2]. Furthermore, thermal signals need to be sufficiently intense, otherwise it can be difficult for users to perceive them correctly, if at all [16]. As well as these human factors, there are also the limitations of thermal electric coolers (TECs), the technology used to deliver thermal feedback in most research. TECs typically have high power consumption, slow rates of change, and large heat dissipation.

However, these limitations do not render thermal feedback useless. There remains an opportunity to use this channel of communication for tasks that require feedback only every few seconds. With their low resolution and slow refresh rate, a potential advantage of thermal displays is that they do not require significant focused attention from the user and can present information in an ambient manner [17]. This paper's contribution is to experimentally demonstrate that temperature feedback can effectively guide on-going behaviour. We developed a Thermal Array Display (TAD), consisting of three TECs worn on the arm, which can display patterns of warm, cool, and neutral temperatures [11]. This paper presents a laboratory-based experiment that demonstrates how continuous thermal feedback provided by the TAD can improve user performance in a navigation task. Unlike previous research, we did not reset the TECs to a neutral temperature prior to sending the thermal signals.

BACKGROUND
User preferences for feedback modality can vary by location and situation. While vibrotactile feedback (VTF) is effective in many situations, it is not appropriate in noise-sensitive environments, such as libraries, and is also less effective in loud and bumpy environments, like trains [3]. Thermal feedback can be silent, depending on the technology used [14], and does not require users' full attention. An in-situ evaluation of PocketNavigator [10] further identified a number of issues using VTF for navigation. Participants often found VTF irritating and they had to learn how to interpret the VTF cues. Although distraction was reduced, participants still looked frequently at their mobile displays: "our results confirm that distraction is a challenge" (pp. 7-8).

Researchers have proposed that temperature cues could also be used to guide navigation. Wettach *et al.* argued that temperature could be a good interaction modality for 'calm technologies' that provide ambient signals, particularly in the domain of navigation, as thermal cues can provide "a rough clue about the intensity of a certain signal or entity" [13 p.2]. However, no outcomes were reported from their study other than "the user was able to find her way to the destination…" [p.2]. No controlled studies have been carried out on other thermal navigation prototypes that have been developed. Lécuyer *et al*. [5] proposed a device indicating sun direction to visually impaired users, but did not evaluate the potential of using both heat and cool cues to guide navigation. Quido [1] used both thermal and VTF to guide participants towards a goal in a 2D maze. While their results showed that performance improved over time, they did not investigate the relative contribution of the two modalities to guide behaviour. Hiya-Atsu [8] investigated a spatial navigation task where users searched for an object on a computer display with a temperature augmented mouse. While all participants found the hidden objects, no details were reported about how the device was evaluated. Our aim was to address the limitations of previous research by investigating the efficacy of temperature changes to guide navigation in a controlled laboratory experiment.

HARDWARE OVERVIEW

The Thermal Array Display, or TAD, is shown in Fig. 1. It is worn on the arm and consists of three stimulators, each one comprising a TEC device (MCPE1-01708NCS, Multicomp), a thermistor (MC65F103A, Amphenol Sensors), a 6V DC fan, and a heatsink. The TECs are controlled by a Proportional-Integral-Derivative (PID) controller on an Arduino Mega 2560 micro-controller. The PID reads the thermistor and sets the output temperature by varying the voltage and direction. Voltage is powered from a 6V, 10A mains supply and is varied using a 490 Hz Pulse Width Modulated signal and smoothed using a choke inductor. A motor driver (MC33926, Pololu) controls the direction, allowing both sides of the TEC to warm up or cool down. This system enables reliable detection of smaller temperature differences than with a single TEC as it both improves error rate and degree of error significantly [11].

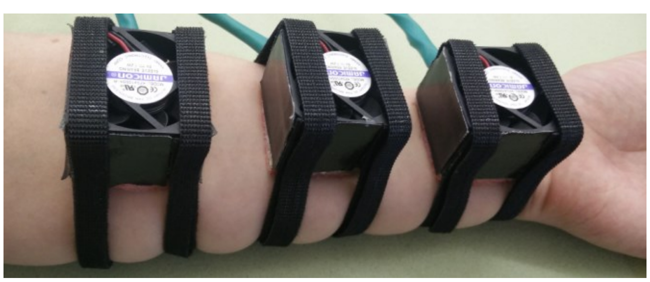

Figure 1. The Thermal Array Display (TAD) consists of three stimulator units, one positioned on the wrist, one under the elbow and the other between them.

EXPERIMENT DESIGN

In the children's game 'Hot-and-Cold', a temperature metaphor is used to guide players towards the location of a hidden object. We hypothesised that actual temperature changes on the skin could provide similar proximity information in a navigation task: increasing heat could indicate getting closer to a goal; conversely, increasing cold could let a user know they are moving further away. To test this hypothesis, we developed a 2D maze navigation task and in a controlled experiment compared user navigation performance with and without thermal feedback.

A participant is represented by a red dot in a 2D maze displayed on a computer display (Fig. 2). They control their position by moving from one path block to an adjacent one using the keyboard arrow keys. Participants were instructed to make as few moves as possible and to try and find the goal within a time limit of ten minutes. The goal, represented by a green dot on the screen, was hidden somewhere inside the maze, and only the local area around the player's current position was visible, the rest of the maze being blacked out. Fig. 2 shows a 3x3 block section of a maze visible to the user on screen, with the surrounding area left semi-transparent in the image—rather than blacked out—to show the maze.

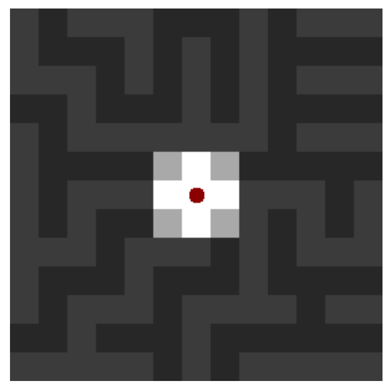

Figure 2. Participants (represented by a red dot) could only see the maze in the immediate area around their current position and the rest of the maze was blacked out (left semi-transparent in this image to show the underlying maze design).

Thermal Feedback Design

Wilson *et al.* used a temperature range of 22°C-38°C [15], a safe and comfortable zone of temperatures appropriate for thermal feedback. As our apparatus has a rate of change of about 1°C/sec, we chose feedback stimuli in the narrower range of 29°C - 35°C to minimize time taken for the TECs to reach the desired temperature.

To design effective thermal feedback for maze navigation, different techniques for correlating temperature changes with a participant's location relative to the goal were explored in pilot studies. We experimented with both *what* was being signalled and *how* it was mapped to temperature changes. We initially tried signalling the current distance from the *global* shortest path between the start and end goal. Pilot study participants found this hard to interpret and often got stuck in a region of the maze. Even if participants did get onto the globally shortest path, they would sometimes head towards the start rather than the goal.

It was more useful to signal distance from the *current* shortest path, recalculated each turn, based on the current position using breadth-first search. We experimented mapping distance from the path to a range of temperatures, with feedback getting colder the further they moved away. However, pilot study participants found these subtle temperature changes and slow rate of change confusing.

It was more effective to use only two temperatures: very warm (35°C) to indicate the participant was on the current shortest path, and very cool (29°C) for when they left the current shortest path. If the user remained on the path, feedback stayed very warm and a change in temperature only occurred if they left the path. The TAD took 6 seconds to cool from 35°C to 29°C given the latency of the TECs, but participants in the pilot usually noticed the cooling and reacted before the minimum temperature was reached. We were interested in determining whether, even with the high latency, lack of re-adaptation, and ambient style feedback, temperature changes would improve navigation in a controlled experiment using 2D mazes.

Maze Design

Several maze designs were explored to determine an appropriate size and complexity: the number of maze junctions that lead to different paths and number of moves needed to go direct from start to finish. We choose mazes of 40x40 blocks, where each block is a single move up, down, left or right. These dimensions were chosen based on the average length of time it took pilot participants to complete a maze without thermal feedback (317.8s, std. dev. 167.9s), meaning we could expect our participants to complete four mazes within an hour session. Four mazes were designed by hand, assisted by an on-line generator: http://www.billsgames.com/mazegenerator/. Each maze design consisted of the same number of junctions, contained no loops, and had a single path from the start point to the goal (global shortest path) of 245 moves.

PROCEDURE

The experiment used a within-subjects design and the order that participants experienced control and thermal feedback conditions was counterbalanced. 12 participants, 9 males and 3 females, all students in the engineering school of a UK university (mean age 31.7 years, std. dev. 6.3 years), were split into two groups. Group 1 wore the device for the first two mazes (feedback condition) and then removed it for the other two (the control condition). Group 2 did not wear the device for the first two mazes and wore it for the last two. In the control condition, a participant had to reach the goal location without any guidance; in the feedback condition, they were provided with thermal cues that informed them whether they were on (very warm) or off (very cool) the local shortest path. Mazes were completed in a pre-determined, randomized order, unique to each participant.

Before navigating any mazes, participants were given written and oral instructions to ensure they understood what the thermal feedback signified and how the controls worked. Participants wore earplugs due to audible sounds from the inductors, as confirmed in the pilots. Before each of the two mazes in the feedback condition started, their skin was re-adapted to a neutral temperature (32°C). However, re-adaptation only occurred before participants started each maze and not while they were navigating the maze.

The time taken to reach the goal and the number of moves made were recorded for each maze. If a participant did not complete the maze within the time limit, they were ‘timed out’ and a cap time of 10 minutes was used. Every move was logged so that we could generate heat maps of participants’ behaviour with and without thermal feedback. After the four mazes were completed, each participant was interviewed about their experience with the thermal feedback.

RESULTS

The mean time to complete mazes with thermal feedback was 249.0s, (std. dev. 115.6s); in the control condition, it was 358.5s, (std. dev. 165.3s). The mean number of moves taken with feedback was 593.5 (std. dev. 321.4); the control condition mean was 1396.0 (std. dev. 577.7). Participants tended to slow down when using thermal cues: on average 2.4 moves per second (mps) were made in the feedback case, whereas 3.9 mps were made in the control condition.

As the data were non-normal, we used a Mann-Whitney non-parametric test to compare performance in the two conditions. This produced U_a=413.5, z=-2.58, p=0.0049 (one sided) when comparing times. Applying the same test to the number of turns taken produced U_a=537, z=-5.12, p<0.0001 (one-sided). Thermal feedback, while of relatively long latency, strongly reduced maze solution time. The low time-out rate across the two conditions did not permit a valid statistical comparison, but the relative counts of 5 (control) versus 1 (thermal) are consistent with the improved performance of using thermal feedback.

In interviews, every participant reported that they understood the thermal feedback and found it easier to find the target with temperature cues: “the temperature feedback helped me to predict where the target was” [P11]; “it’s like a guide to the right path” [P6]. All participants reported that the temperatures were comfortable, P12 said “it was at a level that lets you just feel it”. Participants used temperature changes, rather than the absence or presence of feedback to guide their navigation: P3 reporting “it’s not too hot or cold but there’s enough of a difference to tell them apart.” Some participants emphasised it had taken time to learn the feedback, P5 saying “once I got used to it, I went a bit slower”. There is statistical evidence of a learning effect between the first and second maze. Discarding all pairs that include an unsuccessful attempt (timed out), the average time using thermal feedback fell from 248.2s to 198.0s (std. dev. 75.0s); in the control condition, performance was 355.3s vs 337.3s. The latter was not significant. Improvement with thermal guidance was normally distributed and a pair-wise t-test proved significant (p=0.01, t=2.65, df=2).

Fig. 3 shows 'heat maps' for Maze #2: the start position is bottom right and the target is bottom left. The left image shows P6's moves without thermal feedback, using a strategy they described as, "just try all available paths – some of the paths, I visited them 3 or 4 times". Seven participants reported using this 'exploration' strategy in the control condition. Two reported that they did this systematically—e.g. always turning the same direction at a junction—while others admitted they were more random. Three users said they tried to memorise the maze, but P5 admitted, "I tried to remember the junctions but it was too difficult". Fig. 3 (middle) shows P4 navigating with thermal feedback and it can be compared to the global shortest path shown in blue (right). Thermal feedback reduced exploration of the maze, indicating when participants left the path and thereby reduced their exploration of blind alleys. However, some participants still turned in the wrong direction at some junctions and took some time to return to the correct path. P8 said "sometimes I couldn't distinguish the difference so I had to continue further to understand is it cold or warm". Participants had to learn to adapt to the latency of the feedback, by slowing their rate of movement and seeing how the temperature changed when they took a certain path. P10 expressed frustration that they "had to keep turning around" and expressed a preference for navigation cues that more actively guided them, rather than feedback after the path was left. P1 was more comfortable with the ambient feedback, saying "[you] can't always rely just on temperature – it's more of a complementary hint – I still need to trace the maze in my head".

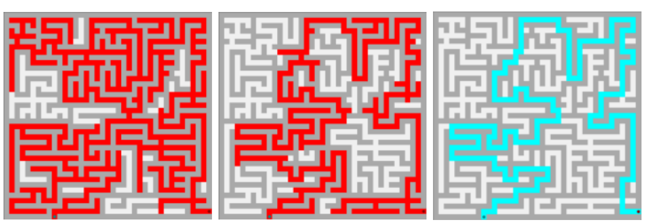

Figure 3: Heat Maps for Maze #2. Left: P6's moves without thermal feedback; Middle: P4's moves with thermal feedback; Right: the global shortest path from start to end.

We asked participants if they felt the thermal feedback could be useful for pedestrian navigation, and all agreed it could be. Two said the device would have to be smaller. The subtlety of the feedback gave rise to differing opinions on how useful it would be in a real-world environment, with three participants suggesting that VTF might be more effective and one stating that, "with this system you will be able to look around" [P3].

DISCUSSION

Given the high latency of the feedback provided to participants, how were they able to use temperature information to improve navigation? First, the feedback was simple to understand, using a warm temperature to inform participants that they were on the right path and a decrease in temperature only when they left the shortest local path. Second, though it took six seconds for the TAD to change between the warmest and the coolest temperature, most participants detected the temperature change before the extremes were reached. Participants all found the feedback useful, but they needed to initially learn how to interpret the temperature changes.

The feedback is similar to a method previously used to successfully guide a complex real-time behaviour using VTF, specifically the bowing action of children learning the violin, who were 'buzzed' when their bow left the desired trajectory [7]. A key difference is that participants reported using both the thermal cues to navigate, rather than relying on the absence or presence of feedback. Future work can explore how the TAD could provide more complex thermal signals to indicate direction as well as the distance from the optimal path.

Our results are particularly relevant for the design of mobile interfaces for pedestrian navigation. Continuous thermal feedback could provide ambient cues for pedestrian exploration of urban areas. It could indicate both a route to follow and the presence of points of interest while tourists can focus on their environment, rather than their mobiles, and make serendipitous discoveries [12]. Given the slower speed that people walk compared to the rate at which participants could move around the maze, the high latency of the feedback may be less of an issue for real-world pedestrian navigation. Temperature could also potentially provide anticipatory navigation cues for drivers, as some drivers' seats and steering wheels already have heating elements built in, although it's not currently clear whether they would be suitable for communicating salient temperature cues. Future work will investigate whether our findings will transfer to noisy and challenging real world environments [16].

More generally, the interview data suggests the potential of using temperature to convey ambient information - a sensory channel that stays in the periphery of a users' attention and only shifts to the centre of attention when necessary. Whether thermal cues are less distracting than other feedback modalities needs verification, but our participants reported barely feeling them.

CONCLUSION

Our controlled study demonstrates the effectiveness of continuous thermal feedback for guiding behaviour, without having to pause between signals to re-adapt the skin. In contrast to previous work that only demonstrated the potential of using temperature feedback for navigation, we provide the first experimental evaluation of simple thermal cues for guiding navigation in a 2D maze. Given the latency of the thermal feedback and lack of re-adaptation between signals, it was not clear whether it would be effective, but our results show thermal feedback enhances navigation performance in a 2D maze task, compared to when there is no feedback.

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