Haptic Navigation Cues on the Steering Wheel

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ABSTRACT

Haptic feedback is used in cars to reduce visual inattention. While tactile feedback like vibration can be influenced by the car's movement, thermal and cutaneous push feedback should be independent of such interference. This paper presents two driving simulator studies investigating novel tactile feedback on the steering wheel for navigation. First, devices on one side of the steering wheel were warmed, indicating the turning direction, while those on the other side were cooled. This thermal feedback was compared to audio. The thermal navigation lead to 94.2% correct recognitions of warnings 200m before the turn and to 91.7% correct turns. Speech had perfect recognition for both. In the second experiment, only the destination side was indicated thermally, and this design was compared to cutaneous push feedback. The simplified thermal feedback design did not increase recognition, but cutaneous push feedback had high recognition rates (100% for 200 m warnings, 98% for turns).

CCS CONCEPTS

• **Human-centered computing → Haptic devices**;

KEYWORDS

Thermal; audio; cutaneous push; haptic; in-car; feedback

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1 INTRODUCTION

One of the major contributors to car crashes and near-crashes is inattention towards the road ahead [4]. Yet most information in modern cars is presented visually and often distributed over several locations such as instrument cluster, centre stack, navigation devices and docked smartphones. The use of these devices during driving competes for the visual attention of the driver, increasing the risk of incidents. Minimizing the visual presentation of information in the car can be achieved by using audio feedback. However, this is not always desired, for example when the feedback interrupts a conversation, music, or radio programme. Furthermore, it is not feasible for hearing impaired drivers. Haptic feedback, however, can be presented unobtrusively and to the driver alone. A well investigated area is the use of vibration. It has been studied for different purposes, such as navigation [3, 7, 11] and warnings [5, 6]. Additionally, vibrotactile feedback has been tested alone [3, 11] and in combination with other modalities [5, 6]. However, the vibration location can be hard to pinpoint [3] and the natural vibration of the car can mask it. Thermal feedback should not share these

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disadvantages and its characteristics have been investigated for mobile devices [14–16], with a recognition rate for direction of temperature change (warming or cooling) of over 90%. Additionally, its use was tested for lane changes in a driving simulation [2], where participants changed correctly 88.57%.

We ran two experiments that investigated the use of thermal feedback on the steering wheel for navigation. Many cars already have heated steering wheels and seats, so temperature changes are familiar to drivers and the exact temperatures of these locations could easily be measured and used as the base temperature for the feedback. The thermal feedback in the first experiment was tested against audio navigation, a standard, widely used non-visual alternative. Participants completed two simulated driving navigation scenarios, using thermal in one and audio in the other to look at feedback use across sensory modalities. A second experiment was conducted to test a simplified, one-sided version of the thermal feedback and compare it to another tactile feedback type: cutaneous push. This push feedback consisted of one solenoid embedded inside the steering wheel on each side. These could protrude and tap the driver's palm. The feedback for both types could thus be presented at the same location and in a similar way, evaluating the effectiveness of the cues, while keeping the differences of presentation to a minimum. Our results show that cutaneous push feedback for navigation was very effective and well-liked by participants.

Contributions

- We investigated thermal navigation feedback on the steering wheel;

- We compared thermal navigation on the steering wheel with cutaneous push and audio feedback during a simulated driving task.

2 RELATED WORK

Thermal interaction has been investigated for navigation outside of driving scenarios. Wettach *et al.* [12] conducted an initial study using thermal feedback for pedestrians. The participants were sent out to find a city location by following thermal cues given by a hand held device. This warmed when they walked towards the destination.

The same mapping of warm temperatures indicating the destination was employed by Tewell *et al.* [10]. They assisted participants in finding the path through a two-dimensional maze game. They gave continuous warm feedback and the devices turned cooler when the users left the path leading to the goal. The performance was increased in the thermal condition.

Our thermal design adopted this mapping and presented turning directions by warming the side of the steering wheel corresponding to the direction in which the user should turn. In a set of studies, Wilson *et al.* [16] investigated the characteristics of thermal feedback in detail and outlined design recommendations for the use of different thermal parameters. Rates of temperature change of both 1°C/s and 3°C/s were effective and the detection rate of each was equal, but 3°C/s led to a faster recognition. Warm and cool stimuli, ranging from 26°C to 38°C with a neutral temperature of 32°C, were both effective, but cool temperatures were faster to detect and more comfortable; warm stimuli felt more intense. They also found that the detection time of thermal stimuli in the range they used varied between 2 and 4 seconds, depending on body location, direction and rate of temperature change. When investigating the design of thermal icons, Wilson *et al.* [13] found that even though complete icons were correctly recognized in 82.9% of cases, the two parameters direction of thermal change and subjective intensity (how much and how fast the temperature changed) had the best recognition rates (97% and 85% respectively).

In our previous work [2], we used thermal feedback to indicate lane changes to drivers in a driving simulator. We used a Peltier device on a table in front of participants, which was touched with one finger of the right hand, forcing users to drive one handed. The direction of the lane change was indicated through the direction of temperature change: when the device cooled, the participants should turn to the left, when it warmed, they should turn towards the right side. We identified the return to the neutral temperature as often being misinterpreted as a new stimulus, initiating additional lane changes. Furthermore, the time to complete a lane change was 1.82s slower with thermal feedback than speech. Our results suggested that adding spatial information could enhance the recognition of directional thermal cues.

In our navigation studies in this paper we attached thermal devices onto the steering wheel to enable participants to drive with both hands on the wheel and to add spatial information to the feedback. Additionally, we initiated the audio and push feedback 2s later than the thermal feedback to make up for the delay in recognition. Details of this design are discussed in the Experimental Design sections.

Haptic Feedback in the Car

Tactile feedback has often been used to convey directional cues in driving environments. van Erp and van Veen [11] engaged vibration under the thigh to give navigation cues. The direction of the upcoming turn was defined by vibration of the corresponding side and additional information on the distance to the turning point was encoded in the vibration pattern. This feedback was tested alone and in a multimodal setting adding visual feedback. The workload of drivers was measured with a Peripheral Detection Task (PDT): the recognition of red squares had to be indicated by pressing a finger switch as fast as possible. Their results showed that workload decreased for the tactile feedback compared to the visual display, especially in high workload conditions. Additionally, the multimodal display reduced the reaction time.

The use of spatial information to convey the turning direction and the idea of using different patterns to encode the distance was adapted for our first thermal navigation study. Instead of placing the devices under the thighs, they were attached to the steering wheel.

Kern *et al.* [3] conducted two experiments on vibration on the steering wheel. They added six actuators to a steering wheel and tested it first in a unimodal and then in a multimodal setting. They encountered difficulties in the first experiment, when the participants had to pinpoint the source of the vibration. To make sure that the vibration could be felt independent of the locations of the hands on the steering wheel, they had to use a high intensity of vibration, which vibrated the whole wheel. This made it hard to identify where the vibration originated. In a second study, they added visual and audio cues. Participants preferred the visual + tactile condition and it was also the variation which elicited the better driving performance.

Medeiros-Ward *et al.* [1] used a similar set-up when presenting shear feedback (movement of the skin) on a steering wheel to prompt lane changes. The direction of the lane change was indicated by moving the skin of the fingers towards the desired lane. Their results showed that in conditions in which the drivers were engaged in a phone conversation the tactile feedback was more accurately interpreted. The results also showed that vibrotactile feedback is not the only type of tactile stimulus that can be used effectively in an in-car environment.

Exploring cutaneous push, Shakeri *et al.* [8] prepared a steering wheel with three solenoid pins on each side. These small metal pins protruded from the steering wheel and pushed against the driver's hand to give feedback. The authors showed that presenting patterns on only one hand was better recognized than for two hands, as were patterns with only one or two pins. Even though not all patterns were recognized correctly, all pin activities were detected. In further studies, they showed that the thenar region, the base of the thumb, was preferred by most participants and caused a lower error rate. Engaging one pin showed 92.2% accuracy [9].

We adapted this feedback type for our second study and used it for navigation for the first time and compared its performance to that of thermal feedback.

The thermal design of the two studies presented in this paper was influenced by these experiments and was designed to investigate thermal navigation feedback during driving.

Figure 1: Thermally-enhanced steering wheel with small Peltier elements.

The advantage of thermal feedback is that it should not be affected by car vibrations. It was important both to examine the effectiveness of thermal feedback for navigation purposes and gather subjective feedback on this new in-car interaction type.

The second study investigated a redesign of the thermal feedback and compared it to cutaneous push feedback. This form of haptic feedback has also not been investigated for navigation before, so this paper includes the first study of its use.

3 STUDY 1

The most common form of non-visual feedback for navigation tasks is speech. Therefore, in this first experiment we compared our concept of thermal navigation against this, using audio navigation as state-of-art and baseline. As navigation is a planned task, a gradual feedback with a slow detection such as thermal should be as effective as an immediate, low latency feedback such as speech. The slow increase of this thermal feedback could be more suitable for a navigation task than a sudden vocal prompt. The hypotheses for this experiment were:

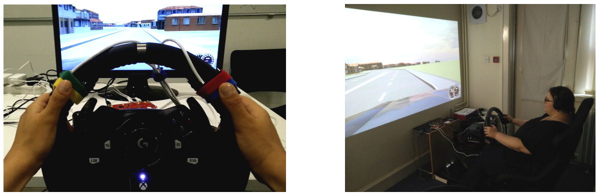
Hypothesis 1: *Thermal and auditory navigation cues will be equally effective in a navigation task;*

Hypothesis 2: *The workload and pleasantness rating (subjective rating) for audio and thermal feedback will not differ significantly;*

Hypothesis 3: *The use of warm (opposed to cool) temperature changes to indicate the destination will be preferred by participants.*

Apparatus

Four 1x1cm Peltier elements with small attached heat sinks were mounted on the steering wheel, as can be seen in Figure 1. On each side, one device was mounted to the front and one to the back. The devices were made by SAMH Engineering and were connected to a computer via USB. For the thermal condition, participants were asked to put the index



(a) Experimental Set-up of first study

(b) Experimental Set-up of second study

Figure 2: The set-up of the navigation studies

finger and the thumb of each hand on the Peltier devices, while gripping the steering wheel.

The study was conducted in a university room, in which participants were seated facing a 23.6-inch HannsG HL249 monitor connected to a DELL XPS 15 9550 laptop using Windows 10. They used a Logitech G920 Driving Force steering wheel securely attached to a table for driving (see Figure 2 (a)). To drown out environmental noises, the participants were asked to wear Sennheiser HD 25-1 II Basic Edition headphones throughout the experiment, which played the audio cues as well as car noises in both conditions. The driving environment was implemented with OpenDS 3.5[1] and depicted a city, which included suburbs with houses as well as city centre skyscrapers, and different numbers of lanes for the streets. This provided a rich environment with sufficient turns to test our navigation cues.

Experimental Design

The study used a two condition, within-subjects design. The Independent Variable was feedback type (thermal, audio). No visual feedback was given to indicate the turning point. The navigation cues were given in two stages, mimicking standard navigation systems: a first warning 200 metres before the turn and then the instruction to turn directly before the turning point. As with the experiments of Wettach *et al.* [12] and Tewell *et al.* [10] the direction in which the participant should turn was presented through warm stimuli on the corresponding side of the wheel. Simultaneously, the opposite side was cooled. We expected this to amplify the overall difference in temperature to increase the distinction between the warm and cold sides of the steering wheel. Additionally, this design was chosen to accommodate one-handed driving: even if one hand was taken off the steering wheel, the remaining hand would still be able to identify the turning direction.

The neutral temperature was set to 30°C and changed by 6°C, with a rate of change of 3°/s for both warnings (based on recommendations from Wilson *et al.* [16]) . This results in 36°C for the devices on the side of the turning direction and 24°C on the other side. The distance to the turn was encoded through the time span in which the stimuli were presented. At the first warning (200m before the turn), the temperature cues were maintained for 3 seconds and then the Peltiers were disabled. Participants were instructed to press the left or right gear paddle on the steering wheel to indicate which way they should turn when they recognized this first warning. This would tell us, if the presentation of the thermal cues could be identified correctly. When the turning point was reached, the temperature was again changed as before and maintained at these values until the turn was completed. Then all Peltiers were set to the neutral temperature and then disabled.

In the audio condition the participants were presented with the phrase “Turn right/left in 200 metres” and then with “Turn right/left” in a synthesized female voice. To compensate for the slower reaction time to the thermal feedback, we started the onset of the audio feedback 2 seconds later than the temperature change. The speech thus was presented at the same time at which the goal temperature was reached. This measure was taken to adjust for the higher latency of thermal feedback as discussed in previous literature [2, 16] and to ensure that the same turning point was indicated by the stimuli.

The car maintained a constant speed of 30km/h to enable a comfortable turn without braking and is a speed limit used in some European cities. Braking and accelerating were not used. This design was chosen to improve comparability between the feedback types. The constant speed eliminated unexpected influences that changes in speed could have on the driving data. The participants were asked to stay within the right-most lane of the street when driving and to ignore any road signs.

The turning points were chosen so that the driver could follow the road straight ahead without the need to turn until the desired turning point was reached. The road usually passed several junctions and crossings, which made it hard to guess the route without feedback. Therefore, the participants were dependent on the feedback to be able to finish the task correctly. Wrong turns were possible at any stage of the experiment.

After every turn (correct or incorrect), the car was reset to another part of the city. This gave the participant ample time to get readjusted by driving straight for several seconds before the next stimulus was presented. The turns were chosen from the four simple junction variations: left-only junctions, right-only junctions, T-junctions and crossroads. One of each of these was used for the two training sessions, in which the participants were made familiar with the experimental set-up before each condition. The main part then consisted of twelve turnings in total, three of each junction type. Two sets

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[1] http://www.opends.eu

of turning points were used to avoid practice effects across conditions. The sets of turns, the corresponding interaction type (thermal, audio) and the order of conditions were all counterbalanced.

The Ethics Committee of our institution approved the study design.

Participants

Thirteen participants (6 female) between 19 and 38 (*Mean*=25.38, *SD*=5.24, *Median*=24) completed this study, consisting of mostly students. Their driving experience ranged between 1 and 11 years (*Mean*=4.88, *SD*=3.11, *Median*=4) with all participants holding a valid driving license. One participant was left handed and none reported sensory or uncorrected visual impairments. The participants showed varied levels of experience with the technologies and interaction types used, which were measured on a scale of 1 (not at all) to 5 (very much). Their experience with the speech navigation was *Mean*=2.92 (*SD*=0.86, *Median*=3), with a driving simulator *Mean*=2.23 (*SD*=1.48, *Median*=2) and with thermal feedback *Mean*=1.85 (*SD*=1.28, *Median*=1). The experience with audio navigation included navigation systems implemented in cars and over smartphones, while the use of racing games was counted as experience with driving simulators.

Procedure

The participants started the experiment by reading an information sheet and signing a consent form. They then filled in a questionnaire collecting demographic data and experience ratings. They were also asked about their preferred mapping for turning direction to temperature. This was not asked directly, but by describing a scenario in which the left side of a steering wheel turns warm and the right side cold. The participants were asked to decide, in which direction they would want to turn.

The participants then drove for a maximum of 5 minutes to familiarize themselves with the driving simulator, the city environment and the steering wheel, without any stimuli being presented. Afterwards, they completed the training and the driving tasks for one condition.

The number of correct recognitions and turns as well as the vehicle path were logged during the main task. These were used to calculate the recognitions rates and the deviation from the ideal path. The deviation from the ideal path was calculated to measure the driver distraction for the indicator warnings 200m before the turn. The ideal path followed the road straight ahead on the right-most lane. Participants followed a road that was not completely straight, as it was influenced by junctions and curves. This ideal path was introduced to measure the lane deviation despite of this irregularity. The deviation was calculated utilizing the Root Mean Square Error (RMSE) of the distances between the ideal path coordinates and the car coordinates, calculated for the 8s before the stimulus begin and 8s from stimulus start.

The participants then filled in both a NASA TLX[2] questionnaire and another questionnaire to rate positive (pleasantness and comfort) and negative (disruptiveness and complexity) aspects of the feedback on a 5-point Likert scale. The participants also had the chance to comment on the experience in the questionnaire. The second condition was completed thereafter. At the end, the participants were asked to answer further questions about the placement and use cases of thermal feedback in a car. They were also asked if using the warm temperature as the indicator for the turning direction felt appropriate. The experiment took one hour to complete, and each participant received £6 for taking part.

Results

Stimuli Recognition. The recognition rate of the stimuli in the speech condition was 100%. The warnings 200 metres before the turn (indicators) were recognized correctly and the turns were completed correctly each time. In the thermal condition the recognition rate was higher for the 200m indicators with 94.2% whereas for the turns themselves it was 91.7%. Of the 156 overall stimuli presentations in the thermal condition 9 indicators were interpreted incorrectly, while 13 turns were done incorrectly. Three of these wrong turns occurred on completely wrong junctions, the other ten were wrong or missed turns at the correct junction. These differences were found significant for the conditions, using Wilcoxon tests, as the data were not normally distributed (Shapiro-Wilks: indicators p=0.002; turns p=0.035): indicators: *Z=2.264, p=0.024*; turns: *Z=2.565, p=0.010.*

Deviation from Ideal Path. The deviation data (compare Figure 3) were not normally distributed (Shapiro-Wilks: thermal (before (b) and after (a) the stimulus presentation): Wb=0.719, pb<0.005; Wa=0.703 , pa<0.005; audio(before/after): Wb= 0.819, pb= 0.012; Wa= 0.852, pa=0.030). Wilcoxon tests showed that the differences within each condition (before/after) were statistically significant, increasing after the stimuli onset (thermal(before/after): *V=0 , p<0.005* ;audio(before/after): *V=1 , p<0.005*). The comparison between them was significant as well (before: *V= 80, p=0.013*; after: *V=74 , p= 0.048*).

Subjective Feedback. The category data of the NASA TLX was captured on a scale of 1 to 10. The overall workload was significantly different *(Z=3.111, p=0.002)* with a median of 22 for the audio and 37 for the thermal condition. Wilcoxon tests confirmed the significance of feedback type for all categories, see Table 1.

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[2] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20000021488.pdf

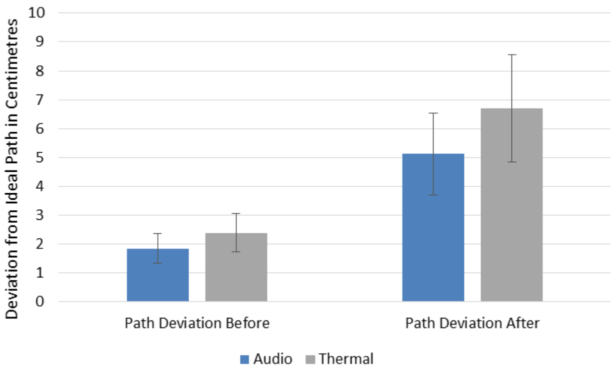

Figure 3: The Deviation from the Ideal Path for indicators (200 metres before the turn). Error bars show the standard error.

Table 1: Results of the Wilcoxon tests for the NASA TLX questionnaires, including the medians for audio and thermal. Significant differences are marked with an asterisk.

	Z	p	median(a)	median(t)
Mental Demand*	3.185	0.001	2.5	7
Physical Demand*	1.966	0.049	3	5
Time Pressure*	2.286	0.022	2.5	4
Effort*	2.789	0.005	3.5	6
Performance*	1.968	0.049	7	5.5
Frustration*	2.833	0.005	2.5	6
Annoyance*	2.593	0.010	2.5	5.5

The subjective ratings of pleasantness, comfort, disruptiveness and complexity (see Figure 4) were evaluated using Wilcoxon tests. The positive aspects (pleasantness and comfort) were significantly higher for the audio condition (pleasantness: *Z=2.289, p=0.022*; comfort: *Z=2.356, p=0.018*), with medians of 4 each in the audio condition and 3 each in the thermal condition.

Additionally, complexity was statistically significantly worse *(Z=2.494, p=0.013)* in the thermal condition, with a median of 1 in the audio and 3 in the thermal condition. Differences in disruptiveness were not significant *(Z=1.916, p=0.055)*, with a median of 2 in both conditions.

In the comment section of the questionnaire P03 reported that they found it *“Difficult to tell temperature differences”* and commented on the *“Uncomfortable hand position”*. P04 mentioned that they *“just registered intensity of temperature rather than intense heat or intense cold”*. Whereas, P10 described thermal feedback as *“very pleasant and soothing”* and P01 wrote that *“As you are more focused on your hands anyway whilst driving it didn’t feel as disruptive”*.

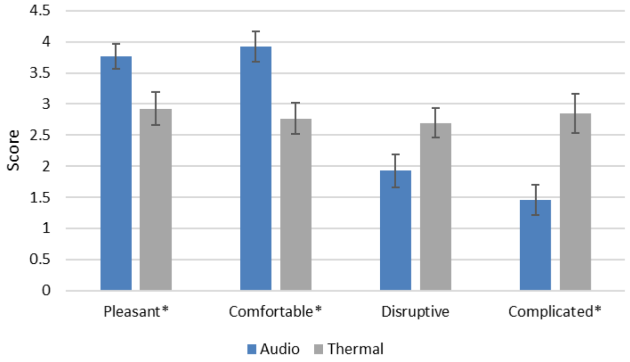

Figure 4: The mean ratings for pleasantness, comfort, disruption and complexity for the Navigation Study. Significant differences are marked with an asterisk, error bars show the standard error.

Turning Direction. When participants were asked at the beginning of the experiment if they would like to turn towards the warm or the cool side: 8 answered warm, while 5 preferred the cool side. At the end of the experiment, after they had to follow the navigational instructions by turning towards the warm, 11 participants reported that turning in the warm direction felt most appropriate and only 2 preferred the cool side. One of these chose the warm side before and changed their mind after having used the warm mapping.

Discussion

The recognition rate for thermal feedback was over 90% for both turns and indicators (200m before the turn). The recognition of the indicators was slightly higher. Nonetheless, when compared to the audio condition with a perfect recognition rate, thermal navigation was still statistically significantly worse. Therefore, *Hypothesis 1*, stating that the two navigation types would be equally effective, was not corroborated. In this experiment the only noise played to the participants was car noises. The disadvantages of audio feedback are more distinctive in noisy environments and thermal feedback could very well outperform audio feedback in that situation. Further experiments are needed to investigate this.

The subjective rating showed statistically significantly worse results for the thermal feedback in all categories but disruptiveness. As *Hypothesis 2* claimed the opposite, it cannot be corroborated. Some of the user comments suggest that the simultaneous presentation of thermal feedback on both hands did not increase the recognition, but instead was confusing, as they had problems distinguishing which side was warmed and which side cooled. Additionally, some participants might have been influenced by the required hand position, as they felt they had to adapt the hand position in the thermal, but not the speech condition. This prototype allowed for two points of contact with the thermal devices on each hand, but the hands had to be in the correct positions. We envision that for the actual application in a car the whole steering wheel could warm and cool and therefore precise hand positioning would be unnecessary.

When asked if they would prefer turning towards the warm or the cool side of the steering wheel, most participants chose the warm side. The majority of participants did not only prefer the mapping hypothetically before the experiment, but also affirmed it afterwards. Therefore, *Hypothesis 3*, predicting the preference of warm, was corroborated.

4 STUDY 2

In this second experiment the thermal design was simplified. As the simultaneous presentation of warm and cold may have confused some participants, this time only the turning direction side was indicated by warming. We expected this to increase the recognition of an upcoming turn. Additionally, the thermal navigation was compared against another novel type of tactile feedback, namely cutaneous push. This feedback has, similar to thermal feedback, the advantage of being independent of car vibrations and can be presented precisely to a small area of skin. Therefore, the feedback design could be presented in the same location as the thermal to allow a controlled comparison, especially of comfort. This leads to the following hypotheses:

Hypothesis 1: *Thermal and cutaneous push navigation cues are equally effective in a simulated navigation task;*

Hypothesis 2: *The subjective rating of comfort of cutaneous push feedback and thermal will not differ;*

Hypothesis 3: *The simplified design of the second thermal navigation feedback will perform better than the design in the first study.*

Apparatus

The study was conducted in a university room, where participants were seated in a gaming racing chair. A Logitech G27 racing wheel mount with a metal steering wheel covered in leather was attached in front of them and connected to a Windows computer. The steering wheel (see Figure 5 right side) had Push Action Tubular Solenoids embedded, one on each side (compare Figure 5 top left). The steering wheel used in the first experiment did not offer space for the solenoids to be attached and had to be changed for this experiment. In the thermal condition, one 2x2cm Peltier (compare Figure 5 bottom left) and a heat sink was attached to each side of the steering wheel on top of the pins. This allowed the participants to have a similar hand position. The bigger Peltier elements were used to make up for the loss of the second point of contact. Unfortunately, the bigger Peltier elements needed to be attached to a bigger heat-sink, which again influenced the grip, leading to a more unnatural hand position. The driving scenario was the same as in the first experiment and was projected onto the wall of the room with a BENQ DLP projector attached to a Windows desktop computer. Sennheiser HD 25 Basic Edition headphones were playing driving noises throughout the driving.

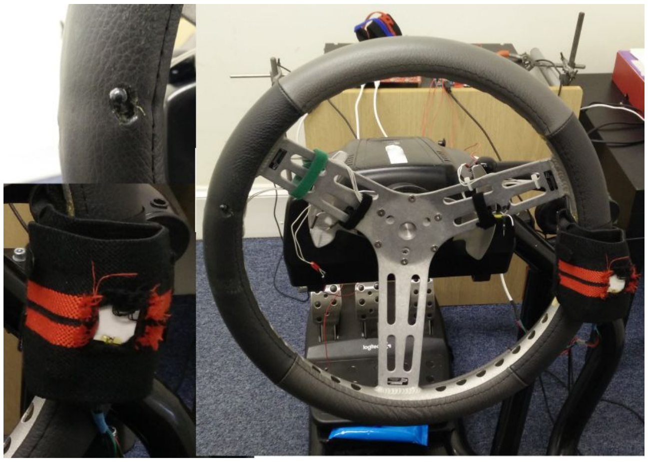

Figure 5: Steering Wheel showing the pin on the left and the Peltier Element on the right side (see pin and Peltier in detail on left side).

Experimental Design

The study was again a within-subjects design with one Independent Variable: modality (thermal, push). The design mirrored the first navigation study. Again, the participants were presented with two warnings: one 200 metres before the turn and the next directly before the turning point. In the thermal condition this first warning was given by warming the side of the turning direction 6°C to 36°C, with a rate of change of 3°/s and from a neutral temperature of 30°C. This temperature was kept constant for 6s and then set back to the neutral temperature with a rate of change of 1°/s. The steering wheel engaged for this study was bigger than the previous one and did not allow the comfortable use of the gear paddles without having to take the hands of it. Therefore, participants were asked to press the accelerator pedal with their foot, when the right side was warming, and the brake, when the left side warmed. When the turning point was reached, the same side would warm up 6°C, and this temperature was kept constant until the turn was completed. It was then changed back to the neutral temperature with 1°/s.

When presenting the cutaneous push feedback, the first warning consisted of engaging the pin on the side of the turning direction, pushing the thenar region of the palm. The pin was kept constant in this position for 6s and then retracted into the steering wheel. When the turning point was approached, the pin would rhythmically protrude and retract with a frequency of 1s until the turn was completed. It was then retracted into the steering wheel.

The driving simulator set-up, as well as the sets of turning points and the training sessions were the same as in the first study and again counterbalanced. The Ethics Committee of our institution approved the study design.

Participants

Seventeen participants (7 female) between 20 and 65 years (*Mean*=29, *SD*=10.35, *Median*=25) completed the study. None of these participants took part in the first study. All had a full driving license, two of them were left-handed and no participant reported sensory impairments of the hands or uncorrected eye-sight. The driving experience ranged between 1 and 45 years (*Mean*=9.12, *SD*=10.49, *Median*=6). On a 5-point Likert scale (1 meaning none, 5 very much) they rated their prior experience with a driving simulator (*Mean*=2.35, *SD*=1.17, *Median*=2), cutaneous push feedback (*Mean*=1.65, *SD*=1.06, *Median*=1) and thermal feedback (*Mean*=1.53, *SD*=0.94, *Median*=1).

Procedure

Participants first were presented with an information sheet and a consent form. They were then seated in the racing chair and introduced to the first modality, followed by the training phase of that modality. The participants did not wear headphones during the training and the experimenter commented on the driving task and the required actions, i.e. pedal press, turn taking and staying in the right-most lane. After the training phase, participants completed the main task, wearing the headphones playing driving noises. The data logged during the main task was used to calculate the path deviation and the recognition rate for turn directions. The path deviation was again calculated for 8s before the indicator stimulus and 8s after the onset. The ideal path was the same as in the first study, as the same sets of turns were used. After having finished the modality the participants filled in the NASA TLX questionnaire and an additional 5-point Likert scale enquiring after the pleasantness, comfort, disruptiveness and complexity of the feedback type. They also had the chance to comment on the experience with free text.

This was followed by the same procedure for the second modality. At the end, they filled in an additional questionnaire, capturing demographic data and ratings, with comment options.

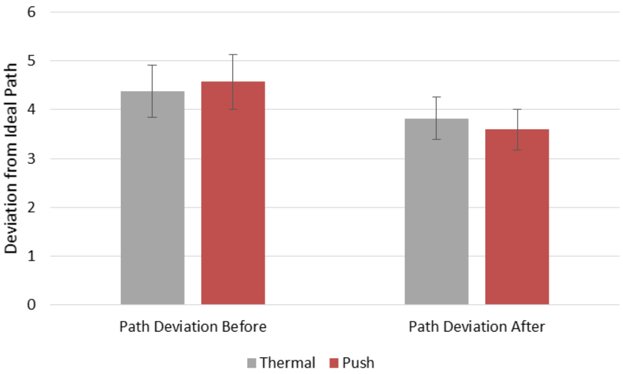

Figure 6: The Deviation from the Ideal Path for indicators (200 metres before the turn), error bars show the standard error.

Results

Stimuli Recognition. The recognition rate for cutaneous push was 100% for the indicators 200 metres before the turn and 98% for the turns themselves. Of 204 turns, four were taken incorrectly. One of these occurred at a completely wrong junction, three were wrong or missed turns of the correct junction.

The thermal condition had a recognition rate of 97.4% for the indicators and 87.1% for the turns. Some participants did not always wait for the second warning and some would sometimes miss a stimulus. In the thermal modality, 26 turns were missed. At nine of those, participants turned into completely wrong junctions, 17 were wrong or missed turns on the correct junction. Four indicators were incorrect or missed in the thermal condition.

The statistical differences between the conditions were compared using Wilcoxon tests, as the data were not normally distributed (Shapiro-Wilks: p<0.0005 for all data sets). The indicators showed no significant difference, whereas the turns did (indicators: *Z=1.414, p=0.157*; turns: *Z=2.488, p=0.013*).

Deviation from Ideal Path. The RSME of the distances, see Figure 6, were compared using Wilcoxon tests, as most data sets were not normally distributed (Shapiro-Wilks: thermal(before/after): W*b*=0.889, p*b*=0.044; W*a*=0.911, p*a*=0.105; push(before/after): W*b*=0.836, p*b*=0.007; W*a*=0.811, p*a*=0.003). There were no statistically significant differences between the two conditions (before: *Z=0.071, p=0.943*; after: *Z=0.402, p=0.687*), but within the conditions (thermal(before/after): *Z=2.769, p=0.006*; audio(before/after): *Z=3.385, p=0.001*). The path deviation decreased, when the stimuli were presented, while they increased in the first study.

Table 2: Results of the Wilcoxon tests for the NASA TLX questionnaires, including the medians for audio and thermal. Significant differences are marked with an asterisk.

	Z	*p*	median(*t*)	median(*p*)
Mental Demand*	3.630	<0.0005	7.5	3
Physical Demand*	2.140	0.032	3	2.5
Time Pressure*	2.232	0.026	4	2.5
Effort*	3.060	0.002	6	2.5
Performance*	2.486	0.013	7	8
Frustration*	2.644	0.008	6	3
Annoyance*	2.729	0.006	4.5	1.5

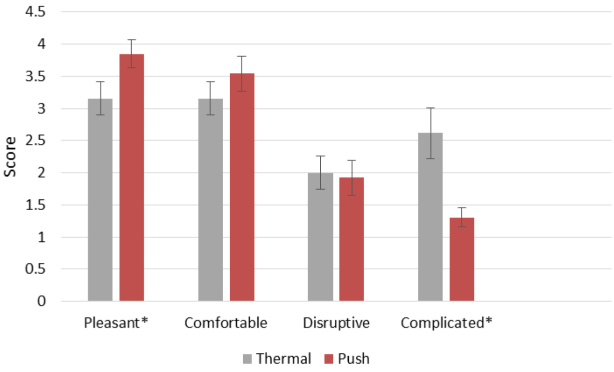

Figure 7: The mean ratings for pleasantness, comfort, disruption and complexity. Significant differences are marked with an asterisk, error bars show the standard error.

Subjective Feedback. The results of the NASA TLX questionnaire (on a scale of 1 to 10) were evaluated using Wilcoxon tests, see Table 2. The thermal feedback was rated significantly worse than push feedback in all categories.

The subjective ratings (see Figure 7) were not normally distributed and evaluated with Wilcoxon tests. Both disruptiveness and comfort were not significantly different for both conditions (disruptiveness: *Z=0.240, p=0.811, median(t)=2, median(p)=2; comfort: Z=1.155, p=0.248, median(t)=3, median(p)=4*), whereas pleasantness and complexity were better for push feedback (pleasantness: *Z=2.209, p=0.027, median(t)=4, median(p)=4*; complexity: *Z=2.969, p=0.003, median(t)=2, median(p)=1*). Overall, only one person (P08) preferred the thermal feedback to push feedback. They named as their reason in the comment section of the questionnaire that with thermal feedback they *"found it less distracting than cutaneous feedback"*, while the cutaneous push *"was a bit disorientating"*. One comment by P14 caught a sentiment on thermal feedback that was shared by others: *"It was good, but not as good as the push warnings, because i had to actively pay attention for it and it was less noticeable. When I did notice the side of the wheel had warmed up, I often wondered if I just noticed the change, or if it had already been like that for a couple of seconds and I had missed it"*. P01 claimed, the thermal feedback *"sensation snuck up on me."*, again pointing out the gradual nature of thermal feedback used in our study. Cutaneous push was described as *"easy to follow, clear signalling, no attention necessary to be certain about signals"* by P07. Most of the participants shared this view. P11 commented on the advantage of haptic feedback overall: *"I like the idea of being able to listen to the radio or talk with people without being interrupted by the satnav's voice"*.

Comparison of the Thermal Feedback Designs. The designs of the first and the second study were compared by evaluating the recognition rate and the subjective ratings. The path deviation could not be compared directly, as two different steering wheels were used for the studies and variation in steering behaviour of the hardware could not be excluded.

The data were evaluated with Mann-Whitney tests and found no statistically significant differences for the recognition rate of both indicators and turns (indicators: *U=75.5, p=0.083*; turns: *U=110, p=0.996*).

Additionally, the evaluation of the subjective measures with Mann-Whitney did not show a statistically significant difference for the results of the workload (Mental Demand: *U=76.5, p=0.156*; Physical Demand: *U=87.5, p=0.344*; Time Pressure: *U=110, p=0.992*; Effort: *U=101, p=0.701*; Performance: *U=67, p=0.069*; Frustration: *U=109, p=0.479*; Annoyance: *U=89, p=0.378*) and the additional ratings (pleasantness: *U=94.5, p=0.481*; comfort: *U=78.5, p=0.178*; disruption: *U=68, p=0.069*; complexity: *U=97.5, p=0.606*).

Discussion

As in the first experiment, the recognition of the thermal feedback was statistically significantly lower for the turns. While some of the turning errors for both conditions originated from not following the instructions given, there are still a few more errors in the thermal condition. Therefore, *Hypothesis 1*, claiming equal effectiveness for both conditions, could not be corroborated. Some of the errors made in the push condition resulted from participants immediately trying to turn at the onset of the stimulus, even if they had already almost completely passed the road at the start of the stimulus. This kind of risky, unchecked turning behaviour was not seen in the thermal condition.

While the workload rating in the push condition was consistently better than the thermal condition, the additional questions showed no statistically significant difference for comfort and disruptiveness, even though the comfort rating is slightly higher for cutaneous push feedback. Therefore, *Hypothesis 2*, stating that the comfort rating would not differ

for both conditions, could not be corroborated. Both conditions here were dependent on correct hand positioning, enabling the feedback types to be more equally compared. Still, participants commented on the uncertainty of the thermal stimuli, which did not occur in the push condition.
When comparing the two thermal navigation designs there were no significant differences in performance with the 200m indicators or the turns. The change from two-sided to one-sided design did not change the recognition rate, opposite to the claim of *Hypothesis 3*. Furthermore, there was no statistically significant difference in the subjective rating between the two thermal designs. The second design was simpler and would require less hardware in the steering wheel, so our results would suggest that, if thermal feedback is to be used, this design would be the most appropriate.

5 OVERALL DISCUSSION

This research tested tactile navigation on the steering wheel. First, thermal feedback, presenting warm and cold stimuli simultaneously, was tested against audio feedback. The turning direction was indicated by warming the corresponding side on the wheel, while cooling the other. Participants commented on the confusion caused by this stimuli presentation. Therefore, in a second study only one side of the steering wheel was warmed and compared to cutaneous push feedback. The recognition rate for indicator warnings 200 metres before the turn and correct turns themselves were not increased by the change in design in the thermal condition: they were between 87% and 97% for both studies. Furthermore, the subjective rating did not change significantly after the change in thermal design. Audio feedback had a perfect recognition rate, however, the scenario was chosen to reflect a quiet scenario, where audio navigation was only accompanied by car noises. In noisy environments thermal feedback would not be influenced, while audio feedback might decrease in performance. This should be tested in further experiments. The push feedback in the second experiment had 100% recognition rate for indicators 200 metres before the turn, but only 98% for the turns themselves.

Audio and cutaneous push feedback both have been shown to be clear and easy to understand. Furthermore, they were detected quickly and with high accuracy. Thermal feedback, on the other hand, showed a slower and gradual detection and was described as more confusing and producing a level of uncertainty. Participants were sometimes unsure, if they had felt a temperature change and they had to concentrate more on the feedback. This uncertainty was increased by the high latency of thermal feedback. With both audio and push feedback they could be confident and certain. Cutaneous push and thermal feedback target the tactile senses which are not usually involved in driving related activities and are therefore ideal for presenting additional information. For navigation purposes, cutaneous push clearly outperformed thermal feedback. However, participants commented on the gradual nature of thermal feedback. This suggests that thermal feedback might be more suited to convey information to the driver that only changes gradually or does not require an urgent response. Participants gave some examples for these applications: *"How close I am to destination. Road ice or grip/traction conditions so I know to drive more carefully"* (Study 1 P11), *"When gas is running low"* (Study 1 P06), *"Handbrake still on"* (Study 2 P09). These suggestion will be considered for future studies investigating thermal in-car feedback.

6 CONCLUSION

This paper investigated tactile navigation feedback on the steering wheel in two studies. In the first, thermal feedback was compared to speech, in the second, a simplified thermal design was compared to cutaneous push feedback. While audio and push feedback had better recognition rates, lower workload and was overall rated more positively by participants, some of the subjective feedback comments pointed out the less disturbing and gradual nature of thermal feedback. Furthermore, the recognition rates of both thermal designs were between 87% and 97%, making them effective for many applications. However, cutaneous push feedback outperformed thermal feedback with recognition rates between 98% and 100%, proving to be a very effective tactile feedback for navigation.

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