Evaluation of Haptic Patterns on a Steering Wheel

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ABSTRACT

Infotainment Systems can increase mental workload and divert visual attention away from looking ahead on the roads. When these systems give information to the driver, providing it through the tactile channel on the steering wheel might improve driving behaviour and safety. This paper describes an investigation into the perceivability of haptic feedback patterns using an actuated surface on a steering wheel. Six solenoids were embedded along the rim creating three bumps under each palm. A simulated driving study was conducted to test for recognition accuracy of the haptic patterns (81.3%). There was no significant increase in lane deviation or steering angle during haptic pattern presentation. These results suggest that drivers can reliably distinguish between cutaneous patterns presented on the steering wheel. Our findings can assist in delivering non-critical messages to the driver (e.g. driving performance, incoming text messages, etc.) without decreasing driving performance or increasing perceived mental workload.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; User Interfaces — Haptic I/O, Interaction styles, and Evaluation/methodology

Author Keywords

Haptic feedback; feedback pattern characteristics; steering wheel; driver distraction.

INTRODUCTION

Car user interfaces are presenting an ever increasing amount of information to drivers, shifting attention away from driving, increasing distraction and causing accidents [14]. Dingus et al.'s [8] 100 car study reported that nearly 80% of all crashes and 65% of all near-misses involved driver eyes-off-the-road distraction prior to the event. Dingus et al. [8] classified an effective 4 seconds of distraction, where eyes are off the road and engaged either in driving-related secondary tasks (e.g. checking the speedometer), or tertiary tasks (e.g. talking to passengers, operating a hand-held device, etc.) [8].

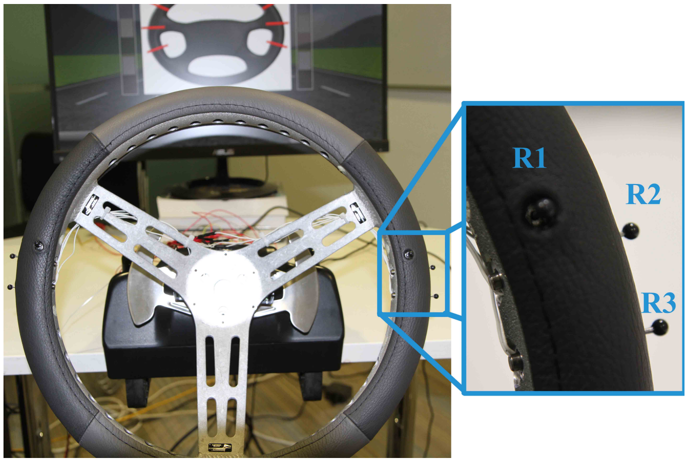

Figure 1. Left: The haptic steering wheel with six solenoids embedded into the rim (three on each side). Right: Close-up of the activated pins on the right side.

One way to reduce infotainment system-based distractions, reduce eyes-off-the-road time and potentially reduce accidents is to provide information non-visually, for example by using haptic feedback. Previous studies have shown that haptic feedback can improve the performance and response to user interfaces [21] while reducing visual workload. It has been shown that tactile feedback in cars does not increase reaction time (RT) [25], does not increase perceived mental workload [25] and is preferred by most users over visual feedback when combined with other modalities [18, 21, 25]. Further, tactile feedback combined with an auditory stimulus is very effective in capturing a driver's spatial attention from a highly perceptually demanding task [16].

Haptic feedback could be presented to drivers in many different ways. The steering wheel is one of the most suitable as they should be holding it all the time when driving. Feedback from the wheel could be presented to different locations on the hands of the driver, e.g. the fingertips, the entire finger, the palm, and the thumb. Research has shown that information can be perceived when presented cutaneously via the skin[22] and provides distinguishable directional information [2]. However, since the fingers contribute to gripping the wheel [1], providing haptic information to the finger-tips may result in decreased grip and thus loss of control. A possible alternative is cutaneous feedback presented to the palm of the driver.

The work in this paper presents the design and evaluation of a haptic feedback system which displays patterns on the steering wheel to the palms of the driver (see Fig. 1). We make fol-

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lowing contributions: (1) we designed novel cutaneous push feedback patterns to the palm; (2) we evaluated the characteristics of haptic patterns presented on a steering wheel; and (3) we investigated whether haptic patterns affect driving performance. Our findings suggest that cutaneous push feedback on the steering wheel can be an effective haptic display in cars, conveying perceptible haptic patterns without negatively affecting driving performance.

RELATED WORK

Previous research has examined numerous types of haptic feedback in cars. These range from vibrotactile feedback in the driver's seat [15], to the seatbelt [3], to vibrotactors on the body [16], and to various types of vibrotactile steering wheels [17, 5, 23]. One benefit of presenting haptic feedback on the steering wheel is that the hands are generally in constant contact with the wheel so it offers an optimal surface for tactile input.

Hwang et al. [17] proposed a "Haptic Wheel", which was a vibrotactile display with 32 linear actuators embedded into it. These actuators presented information such as *alert*, *turn left*, and *turn right* to the driver. Furthermore, information was coded with spatial and temporal patterns. This design allowed for information presentation regardless of holding posture and number of hands gripping the wheel. The recognition rate of the presented patterns was very high (88% to 93%). 450 ms per pattern resulted in the highest recognition rates. Up to six actuators were involved in directional stimuli, i.e. *turn left*. Studies evaluated the users' ability to recognise the patterns correctly, but not their effect on driving.

Another vibrotactile steering wheel was presented by Sucu et al. [23]. Their wheel indicated in which direction and how far to steer in order to facilitate steering without visual feedback. This steering wheel interface allows for blind steering through small (45°) curves. It improved lane keeping behaviour when combined with visual feedback. Kim et al. [19] presented a haptic steering wheel with 20 vibrotactors. Directions were presented by activating the vibrotactors in either clockwise or anticlockwise patterns. Their user study found significant improvement in driving performance when haptic feedback was provided.

Enriquez et al. [9] were the first to implement a kinaesthetic display on a steering wheel. Their steering wheel uses pneumatically inflatable balloons underneath the driver's hands to alert the driver. The steering wheel showed promise in delivering valuable driver notifications. However, their approach had limitations: the pneumatic balloons were 10 cm long and provided only binary warnings. Furthermore, the time necessary to inflate the pneumatic balloons rendered this system only usable for non-critical events.

Allan et al. [2] investigated the usability of a "sandpaper-like rubber tactor" on the steering wheel under the index finger. This button deformed the skin in different directions to give navigation cues. Their approach was successful but had limitations. It only facilitated navigational tasks; no additional information was displayed. Furthermore, they did not test whether the tactor affected driving performance.

Haptic patterns produced by solenoids on the steering wheel were introduced by Shakeri et al. [22]. Three solenoids were embedded into the rim of the wheel (covered by a latex sheet) and presented haptic patterns to the median palm. Their results showed that participants could distinguish up to three pin patterns with 62.7% recognition accuracy. Their experiment had some limitations: (1) the cutaneous push feedback provided by their solenoids was only to the median palm only rather than to a wider part of the hand, potentially reducing effectiveness, (2) they used weak solenoids (2.9 N max) which did not provide strong and clear cues to participants, and (3) the latex sheet used to cover the solenoid pins had a dampening effect on the push force of the solenoids and reduced accuracy of perception. They did not analyse any driving data, thus it is unknown whether the presentation of haptic patterns caused a decrease in driving performance.

Research has shown that haptic feedback from the steering wheel enables robust and efficient communication [18] and that haptic messages can be perceived [5, 18, 22]. However, vibrotactile steering wheels have limitations: even in laboratory conditions, participants struggle to correctly identify the location of the vibration on the wheel [18] especially when tasked with simulated driving [5]. Torque (force) feedback can remain unnoticed since it can be mistaken for driving related ("natural") torque caused by the road or the tyres [4]. There is little research investigating perceivable haptic patterns that can be conveyed to the driver effectively and reliably, and their affects on driving performance.

DESIGNING HAPTIC PATTERNS ON A STEERING WHEEL

Cutaneous information can be delivered to the gripping palm via an actuated surface (e.g. solenoid pins), which will create skin indentations. Aldien et al. [1] showed for all subjects and cylindrical objects, there is definite contact between palmar region and the gripped object. Cutaneous push feedback from the steering wheel should aim at this area to guarantee skin contact without disturbing grip on the wheel. Primarily the thenar (thumb) and the median palmar region are receptive to pressure stimuli [10] (see Fig. 2). Vallbo et al. [24] have found that the sensory units in the palm are very sensitive to mechanical transients such as skin stretches, taps with finger or pen, etc.

To excite appropriate sensory units on the palm, the optimal skin indentation should range between 2 - 5 mm [20]. When actuated, the pins creating the skin indentation should stick out 5 mm (0 mm when not). The pin states should be binary (up or down) to make the patterns as distinguishable as possible [6] since subtlety in haptic icons causes increased pattern discrimination errors [13].

Gallace et al. [11] showed that up to four vibrotactile stimuli presented simultaneously resulted in nearly error-less identification. However, if the number of stimuli exceeds four, active counting starts, which is slow, error prone and attentionally demanding [11]. These findings are supported by Shakeri et al. [22] who showed that participants struggled to distinguish more than three cutaneous actuators on a steering wheel. Further, the greater the number of stimuli the worse was perception accuracy.

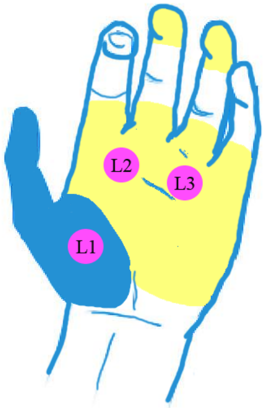

Figure 2. Inner left hand with most sensitive areas to pressure input via a $1cm^2$ round metal pin. Blue (area containing L1): thenar/thumb region. Yellow (area containing L2 and L3): median palmar region. $10-20\%$ less sensitive to pressure input than thumb region. White: fingers are more than 20% less sensitive to pressure input than thumb region [10]. The pink dots indicate where the solenoids were placed.

Craig et al. [7] found that vibrotactile patterns were categorised more efficiently, when the patterns were horizontally mirrored and presented to the fingers on opposite hands rather than on the same hand. Displaying the haptic pattern to both hands created more redundant information which helped during pattern recognition. However, there was more interference (masking and response competition) if the pattern was presented bilaterally (on both hands) rather than ipsilaterally (on the same hand) [7].

Research suggests that cutaneous push feedback patterns from the steering wheel presented to the thenar region will result in higher recognition accuracy than to the palmar region only [10]. This can improve overall haptic pattern perception on the steering wheel. Furthermore, presenting cutaneous push feedback instead of vibrotactile feedback to the palm can overcome the problem of localising the spatial origin of the stimulus on the steering wheel.

METHOD

A perception study was designed to investigate the effectiveness of cutaneous push feedback patterns on a steering wheel in a simulated driving environment. The key aim was to provide insight into the number of active solenoids and characteristics of haptic patterns a driver could distinguish without significant increase in lane deviation and perceived mental workload.

Equipment

The haptic patterns on the steering wheel were created by embedding six solenoids[1] into a pre-drilled metal steering wheel[2] (see Fig. 1). The solenoids were labelled according to the side of the wheel they were on and numbered from top to bottom: L/R1 (top left/right), L/R2 (middle left/right) and L/R3 (bottom left/right), see Fig. 1. Two solenoid pins (R2/R3 and L2/L3) provided feedback to the median palmar region, and one solenoid pin (R1 and L1) provided feedback to the thenar/thumb region (see Fig. 1). The median palmar region and especially the thumb region are most sensitive to pressure input [10] (see Fig. 2). R2-R3 and L2-L3 are 3cm apart from each other, and all the pins come out up to 5 mm. The solenoids exerted a force of up to 4.18 N. Plastic domes/heads (diameter of 0.4 cm) were mounted on the solenoid pins to increase contact area and avoid pain on contact. The steering wheel was securely attached to a Logitech G27 Racing Wheel base, replacing the original steering wheel (see Fig. 1). We chose 3 solenoids for each hand to keep the number of haptic patterns/combinations feasible in our evaluation.

We used OpenDS[3] Version 3 to simulate the driving scenario in the lab. We chose a five lane highway where participants were asked to keep in the middle lane as closely as possible. There was no other traffic, lane changing tasks, cross-winds, road-crowns, etc. to remove any driving task related lane deviations. The results from the driving simulator would inform the level of lane deviation caused by the stimulus presentation and indicate the amount of distraction caused by the haptic feedback patterns.

Stimuli Set

Given six solenoids, with a binary state (in/out), 64 feedback patterns are possible. However, patterns consisting of more than 4 solenoids were not tested due to recommendations by Gallace et al. [12]. The aim of testing this number of patterns was to determine a set of haptic patterns a driver can successfully distinguish. Therefore, 56 (no zero pin) haptic patterns were displayed to the driver. During the experiment, the randomly ordered 56 patterns were displayed at least twice to each participant. There were overall 192 patterns presented to each user throughout the experiment. 1-4 pin patterns were presented each 48 times (i.e. 48 *x* 1 pin patterns, 48 *x* 2 pin patterns, etc.).

Hypotheses

H1: Pins L1 and R1 will have the highest identification accuracy;
H2: An increased number of pins will decrease haptic pattern identification accuracy;
H3: Ipsilateral patterns will be better perceived than bilateral ones;
H4: If patterns are displayed bilaterally, horizontally mirrored ones will have a higher identification accuracy over not mirrored patterns;
H5: No significant increase in lane deviation nor steering angle during and after haptic pattern presentation compared to baseline (driving without any pattern presentation).

Experimental Variables

The Independent Variable was: haptic patterns. The Dependent Variables were: pattern recognition accuracy (if all the pins for each pattern were selected correctly; otherwise, the

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[1] Tubular solenoid. Accessed Feb 2016: http://uk.rs-online.com/web/p/tubular-solenoid/4317532/

[2] Drilled steering wheel. Accessed Sept 2016: http://www.longacreracing.com/products.aspx?prodid=7620

[3] OpenDS driving simulator. Accessed Oct 2015 https://www.opends.eu/

trial was counted as incorrect), perceived mental workload (NASA TLX workload), lane deviation, and steering angle. The patterns had the following characteristics: number of actuated pins, number of hands involved in a pattern, and whether it is horizontally mirrored across both hands (e.g. L1-R1, L2-R2, L3-R3). Furthermore, we measured hand breadth to test for correlations between gender, hand breadth and perception accuracy.

Procedure

Nineteen participants (7 female) aged between 19 and 66 years (μ=27.8, σ=10.3) took part in this experiment. They all held a valid driving license with 1 to 44 years of driving experience (μ=9.1, σ=9.2). 16 participants reported to be right handed and 3 left handed. The participants sat in front of a 27 inch LCD monitor and a PC running the OpenDS simulator. Drivers were able to steer with a Logitech G27 Racing Wheel. Participants wore headphones to mask any sound from the solenoids. Road and car noises from the driving simulator were played through the headphones.

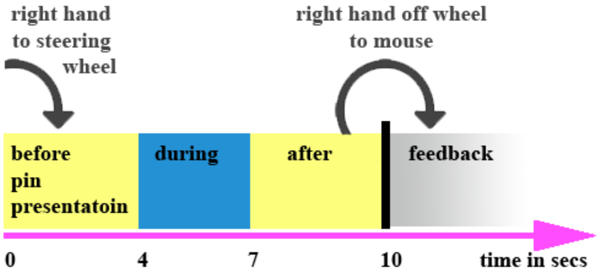

Figure 3. A single trial consists of 4 seconds driving, 3 seconds of haptic pattern presentation, 3 seconds driving after presentation and the user feedback.

The driving task included driving as straight as possible in the middle lane of a five lane motorway. A single trial commenced with 4 seconds of driving, followed by the presentation of a haptic pattern for 3 seconds (as a result of max. 4 solenoids *x* 500-800ms to shift attention from pin to pin [7]), followed by a further 3 seconds of driving (see Fig. 3). The 3 seconds post-presentation provided us with a data, which enabled analysis of whether the haptic patterns affect driving performance *after* presentation. Our pilot studies showed that participants required 4 seconds to return to stabilised driving prior to haptic pattern presentation and 3 seconds post-presentation. The trial ended with the user providing feedback about the perceived haptic pattern by checking the check box next to its associated actuator on the feedback screen (see Fig. 4). Therefore, participants took their right hand off the wheel when prompted with the user feedback screen, and returned it to the wheel once the next trial commenced. This movement caused the prior pin presentation phase to be 3 seconds long. Since this was a perception study, participants were instructed to keep their hands on the steering wheel covering the actuators such that feedback was provided to the regions of the palm as depicted in Figure 2. In future studies the solenoids can be embedded in the entire rim of the wheel to guarantee perception regardless of holding position.


Please indicate which stimuli you've felt.

Figure 4. User feedback screen. Each check box corresponds to a solenoid on the steering wheel. Left top to bottom: L1-L3, right: R1-R3.

Baseline data was collected by participants driving for 2 minutes in the middle lane without any stimulus presentation (e.g. haptic patterns, traffic, lane changing task, etc.). Baseline data was treated as zero pins presented.

At the end of the experiment, we assessed perceived mental workload using the NASA TLX questionnaire.Participants were also asked to answer a set of open questions about the usability of our system, whether they had preferences in pattern characteristics, what characteristics they rated as least/most distracting, and what area of the palm they preferred cutaneous push feedback to be presented to. The whole experiment lasted 90 minutes including introduction and questionnaires.

The main differences of our study to Shakeri et. al's [22] set-up are: (1) presentation of haptic feedback to thenar and median palmar region compared to palmar region only, (2) stronger solenoids (4.18 N vs 2.9 N), (3) no latex sheet dampening the impact of the haptic feedback, and (4) size of the steering wheel (38.1 cm vs 28.3 cm diameter).

RESULTS

Haptic Pattern Recognition

All tested patterns and their specific discrimination rates are listed in Table 1. A Chi-square test revealed significant differences in identification accuracy ($\chi^2(3, N = 3681) = 160.705, p < 0.0001$) regarding the number of active pins in a pattern. Figure 5 shows that with increasing number of stimuli per pattern, pattern recognition decreases.

A one-way ANOVA showed a statistical significance in pattern recognition rate between a number of hands involved in the pattern (F(1,3679) = 95.064, p < 0.0005). If a haptic pattern is presented bilaterally, 76.29% were correctly recognised, whereas 88.72% were correctly identified if presented ipsilaterally. There was no statistically significant difference in pattern identification between left and right handed participants as determined by a one-way ANOVA (F(1,17) = 0.004, p = 0.948). Furthermore, there was no statistically significant difference in pattern recognition accuracy between the individual hands (F (2, 16) = 0.831, p < .0005; Wilk's λ = 0.906, partial η^2 = 0.094). There was no statistically significant difference in

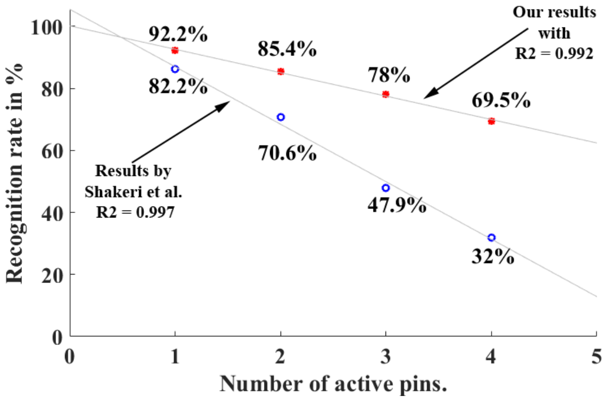

Figure 5. Average recognition rate in regards to pin count. Starred points are results from our study, circle points are results from Shakeri et al. [22]. Linear functions were fitted to the data points: a) coefficient of independent variable $b = -0.1321, R^2 = 0.997$, adjusted $R^2 = 0.996, p = 0.00129$, b) coefficient of independent variable $b = -0.0537, R^2 = 0.994$, adjusted $R^2 = 0.992$, $p = 0.00281$.

Pattern	%	Pattern	%	Pattern	%
110100	97.2	000001	85.4	100111	72.2
010000	95.2	100110	83.3	111010	72.2
100100	95.2	000111	81.9	101101	70.8
011000	94.6	101100	81.1	010111	69.4
001000	94.5	110010	81.1	101011	69.4
000100	94.4	000011	80.6	110001	69.4
100000	92.4	001010	80.6	011100	67.6
010110	91.9	101000	80.6	011101	67.6
000110	91.7	001001	80.0	001111	66.7
000010	91.2	111100	78.9	101001	66.7
010010	89.7	011011	77.4	111001	66.7
100010	88.9	010001	75.0	001101	64.9
110000	88.9	100011	75.0	011110	63.9
110110	87.8	010011	73.0	101010	63.9
111000	87.5	000101	72.2	110011	62.2
001110	86.5	001011	72.2	011001	61.1
011010	86.5	010101	72.2	110101	60.5
001100	86.1	100001	72.2	101110	58.3
010100	86.1	100101	72.2	-	-

Table 1. All tactile patterns and their identification accuracy. The 0 and 1s for each pattern represent (from left to right): L1|L2|L3|R1|R2|R3.

pattern identification given symmetrically mirrored (83.84%) and not mirrored (81.02%) bilaterally presented patterns as determined by one-way ANOVA (F(1,3679) = 3.081, p = 0.079). Finally, participants correctly identified the spatial origin of the displayed patterns (100%).

Pin	Error	Pin	Error
L1	3.97%	R1	3.97%
L2	5.18%	R2	4.96%
L3	8.91%	R3	16.21%

Table 2. Percentage of error rates for each pin, e.g. 3.97% of all L1 pins were perceived incorrectly.

L1 was the best perceivable pin presented to the left hand, and R1 to the right hand (see Table 2). Further analysis showed that 14.39% of right hand patterns were not identified correctly, whereas 9.36% of left hand patterns were not identified correctly.

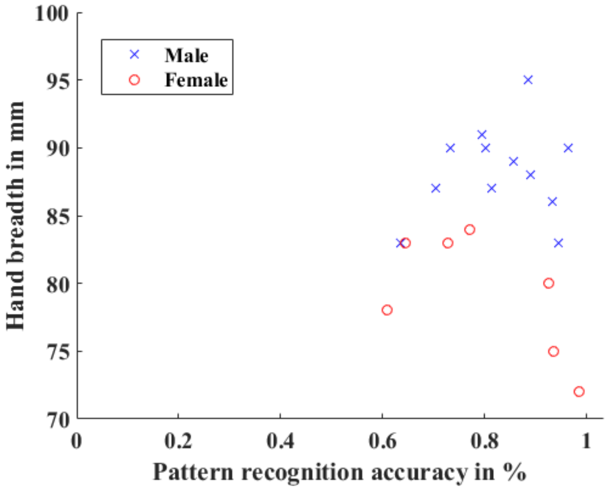

Figure 6. Performance by gender and hand breadth.

There was no significant difference in pattern identification based on gender (F(1,17) = 0.265, p = 0.613) with 80.59% for males and 79.57% for females (12 males, 7 females) (see Fig. 6). A Spearman's rank-order correlation was run to determine the relationship between hand breadth and pattern identification rate; there was no correlation, which is statistically significant (r_s(3458) = 0.003, p = 0.839).

Lane Deviation and Steering Angle

We used the Root Mean Square Error to measure the lane deviation (in metres) for any interval. 4/19 participants deviated to an outer lane immediately after commencing the experiment and stayed there for the remainder of the time. We normalised these data by subtracting the mean of the lane the participants deviated to from the raw data (middle lane $\mu = 0$ m, inner lanes $\mu = \pm 3.7$ m, outer lane $\mu = \pm 7.4$ m).

A Friedman test showed no statistically significant difference between lane deviation between *before*, *during* and *after* haptic pattern presentation ($\chi^2(2) = 989.170, p < 0.0005$), nor in steering wheel angle deviation ($\chi^2(2) = 2969.980, p < 0.0005$).

No of pins	0	1	2	3	4
Before μ	-	0.90	0.90	0.91	1.00
Before σ	-	1.04	1.03	1.02	0.77
During μ	0.31	1.02	1.04	1.03	1.07
During σ	0.76	0.75	0.76	0.73	0.77
After μ	-	0.99	1.04	1.08	0.92
After σ	-	0.73	0.74	0.73	1.03

Table 3. Lane deviation (in meters) for differing numbers of active solenoids (*before*, *during* and *after* pattern presentation). There are no values for *after* presentation of zero pins.

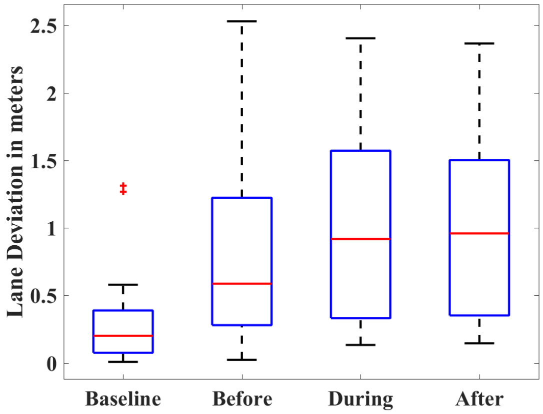

Figure 7. Lane deviation at different times during the experiment. The presented values are averages over all participants.

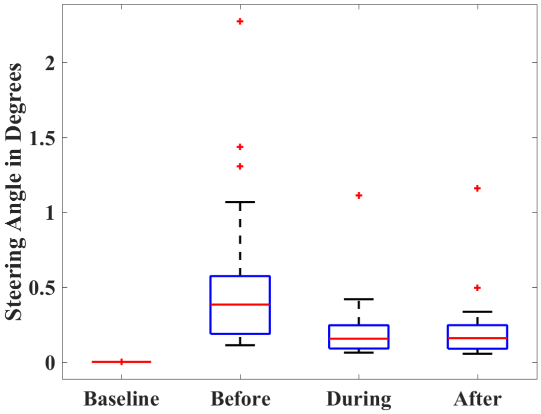

Figure 8. Steering angle deviation at different times during the experiment. The presented values are averages over all participants.

A Kruskal-Wallis H test showed that there was a statistically significant difference in lane deviation given differing numbers of pins (see Table 3) during haptic pattern presentation ($\chi^2(4) = 51.765, p < 0.0005$) with mean ranks for zero (10.50), one (1866.12), two (1865.61), three (1826.93), and four (1816.69) pins. However, there is no statistically significant difference in driving behaviour when 1-4 pin haptic patterns are displayed ($\chi^2(3) = 1.528, p = 0.676$) with mean ranks for one (1847.12), two (1845.61), three (1807.94), and four (1797.69) pins. This suggests, there is only a difference in lane deviation between baseline (zero pin patterns) and any (1-4) pin patterns displayed. Furthermore, steering wheel deviation analysis correlates with lane deviation analysis (see Fig. 7 & 8). A Kruskal-Wallis H test showed no statistically significant difference in steering angle between 1-4 pin patterns ($\chi^2(3) = 5.484, p = 0.140$) with mean ranks for one (1771.65), two (1807.65), three (1844.04), and four (1886.64) pins. However, there was a significant difference in steering angle if 0-4 pin patterns were analysed ($\chi^2(4) = 41.434, p < 0.0005$) with mean ranks of zero (387.50), one (1788.66), two (1824.70) three (1861.08), and four (1903.68) pin patterns.

User Feedback

User preferences regarding position of the pins were as follows: 10/19 preferred R1/L1 over the other pins, 7/19 liked the R2/L2, and 2/19 mentioned R3/L3 to be most preferred. 10/19 participants reported that it was hard to distinguish between the median palmar pins R2/R3 or L2/L3. Least distracting pins were considered L1 and R1 with 6/19. Furthermore, symmetrically mirrored patterns (5/19), ipsilateral patterns (5/19), and single stimulus patterns (4/19) were considered to be least distracting. Other participants did not have any strong preferences.

The most distracting patterns were not symmetrically mirrored patterns (4/19) and patterns presented to the median palm (L2-L3, R2-R3) (5/19). Haptic patterns with less than three active solenoids were rated as less distracting by 16/19 participants. Finally, 9/19 participants found they could increase perceivability of the patterns by moving their hands around and readjusting the grip force.

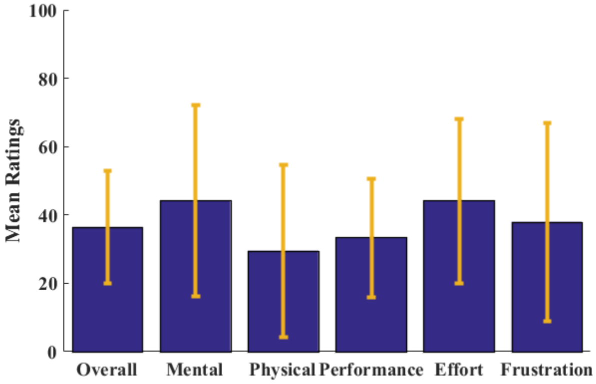

Figure 9. User Feedback from NASA TLX. The error bars represent standard deviation.

Analysis of the NASA TLX questionnaire (see Fig. 9) showed generally low scores, so that participants did find our system mentally or physically demanding.

DISCUSSION

H1: Better Perception on Thumb Region

The results of our analysis are a clear indication that cutaneous push feedback presented to the thumb region did yield the best recognition. Therefore, hypothesis H1 is accepted, since pins L1 and R1 have a lower error rates than the other pins (L1/R1: 3.97%, L2/R2:5.18%/4.96%, L3/R3:8.91%/16.21%). This is due to the thumb region being the most sensitive area to pressure input [10]. Our 4 pin patterns yielded 69.5% perception accuracy compared to Shakeri et al.'s 32% [22]. R3 had poorer perception accuracy because it did not exert as much force as the other solenoids.

H2: Accuracy based on Number of Stimuli

Haptic patterns presented on the steering wheel can be perceived with high accuracy (81.2%). With an increasing number of active pins in a pattern (1 stimulus: 92.2%, 2 stimuli: 85.4%, 3 stimuli: 78%, 4 stimuli: 69.5%), the poorer the pattern discrimination accuracy. Thus, hypothesis H2 is accepted. It is interesting to notice that according to Figure 5, pattern perception rate decreases linearly regardless of solenoid positions or strength (our results vs. Shakeri et al.'s [22]).

H3: Ipsilateral vs. Bilateral Presentation

H3 was accepted since presenting haptic patterns bilaterally decreased identification accuracy from 88.7% to 76.3%. Finally, participants accurately localised the origin of each pattern (whether it was presented to the left or right hand) with 100% accuracy in spatial discrimination of stimulus origin.

H4: Better Perception if Stimuli are Horizontally Mirrored if Presented Bilaterally

Hypothesis H4 was rejected because there was no significant difference in pattern identification accuracy between horizontally mirrored and not mirrored patterns, if presented bilaterally. These findings are contrary to findings by Shakeri et al. [22]. This may be due to our solenoids exerting a greater force (2.9 N vs. 4.18 N), thus they were more distinguishable. Furthermore, Shakeri et al.'s [22] solenoids were covered in an additional latex sheet, which might have blurred the patterns. Additionally, there was no significant difference of haptic pattern discrimination between the hands of participants, which is in accordance with the findings of Vallbo et al. [24].

H5: No Significant Increase in Lane Deviation nor Steering Angle Compared to Baseline

We rejected hypothesis H5 since there was a significant increase in lane deviation and steering wheel angle for *during* and *after* pin presentation compared to baseline. However, there was no significant difference in lane deviation nor steering angle during the three intervals *before*, *during*, and *after* haptic pattern presentation (see Table 3). An explanation for this is that during the baseline phase, participants were driving straight for two minutes without any interference. This provides more data to average out lane deviation over time. During the experimental phase, however, participants only had 4 seconds prior and 3 seconds post haptic pattern presentation. These limited intervals do not average out lane deviation sufficiently to resemble the baseline averages. Therefore, we reject hypothesis H5. However, there were no significant differences found between the *before*/*during*/*after* intervals (see Fig. 7 & 8). We conclude that cutaneous push feedback patterns do not significantly increase lane deviation nor steering angle compared to *before* and *after* haptic pattern presentation.

Usability

Four out of nineteen participants thought the haptic steering wheel could be very useful when combined with a navigation system, since visual feedback is considered distracting by 7/19 participants. 10/19 participants mentioned that the haptic — the "physical" — aspect of interaction was "nice". However, it was mentioned 7/19 times to make the pins stronger and more forceful (i.e. it should not be possible to push the pins back into the casing once the haptic pattern was presented).

Comparison to Previous Research

Shakeri et al. [22] investigated cutaneous patterns on a steering wheel to the median palmar region. Haptic pattern recognition accuracy for their design was 54.6% (1 stimulus: 86.2%, 2 stimuli: 70.6%, 3 stimuli: 47.9%, 4 stimuli: 32.0%) (see Fig. 5). Our steering wheel design yielded 81.2% haptic pattern recognition. This is due to providing cutaneous push feedback to the thenar region instead of the median palmar region only. Further positive influences can come from stronger solenoids and no latex cover dampening the impact of the solenoid pins.

CONCLUSIONS AND OUTLOOK

This paper presented cutaneous push patterns on a steering wheel using an actuated surface. Results showed, that cutaneous push feedback patterns can be conveyed to the driver with high accuracy (81.2%). Our findings provide potential for using haptic patterns for non-critical events such as upcoming traffic conditions, road surface conditions, driving performance, etc. In the future, we plan to explore the design of mapping haptic feedback on a steering wheel to in-car applications such as navigation assistance in a simulated driving scenario. This will study the haptic message perception accuracy and haptic message recall ability in a real world application examining mental workload in more detail.

We came to following conclusions: (1) cutaneous push sensations presented to the thenar region of the palm have the highest identification accuracy; (2) the more stimuli are involved in a pattern, the worse the identification rate becomes; (3) ipsilaterally presented patterns had a higher discrimination accuracy than bilaterally presented ones; (4) horizontally mirroring the pattern bilaterally had no significant effect on perception over not mirrored patterns; (5) participants localised the spatial origin of the haptic pattern very well; (6) presenting haptic feedback patterns to the palm of the driver does not affect driving behaviour significantly compared to *before* and *after* pattern presentation; and (7) there is no difference in haptic pattern discrimination between the dominant and non-dominant hands. Cutaneous push feedback is a novel approach to providing tactile cues on the steering wheel [22], overcoming the shortcomings of vibrotactile feedback in regards to identification of the spatial origin of the stimulus.

The work in this paper presents cutaneous push feedback patterns displayed on the steering wheel. Our findings suggest that cutaneous push feedback can be an effective display in cars, conveying perceptible haptic patterns without negatively affecting driving performance.

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