Evaluating Haptic Feedback on a Steering Wheel in a Simulated Driving Scenario

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Abstract

This paper investigates how perceivable haptic feedback patterns are using an actuated surface on a steering wheel. Six solenoids were embedded along the surface of the wheel, creating three bumps under each palm. The solenoids can be used to create a range of different tactile patterns. As a result of the design recommendation by Gallace et al. [12] maximally four of the six solenoids were actuated simultaneously, resulting in 57 patterns to test. A simulated driving study was conducted to investigate (1) the optimal number of actuated solenoids and (2) the most perceivable haptic patterns. A relationship between number of actuated solenoids and pattern identification rate was established. Perception accuracy drops above three active solenoids. Haptic patterns mirrored symmetrically on both hands were perceived more accurately. Practical applications for displaying tactile messages on the steering wheel are e.g. dead angles, upcoming road conditions, navigation information (i.e. conveying information discretely to the driver).

Author Keywords

Pressure sensing; tactile input; touch interaction.

ACM Classification Keywords

H.5.m [HCI]: Information interfaces and presentation (e.g., HCI): Miscellaneous.

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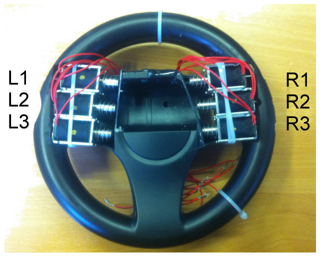

Figure 1: The haptic steering wheel with six solenoids embedded into it (three on each side). The nomenclatur of the solenoids is according to position on the steering wheel, e.g. bottom left solenoid is L3. In the final version, a latex sheet covered the entire surface of the wheel to enlarge the contact area with the user's hands.

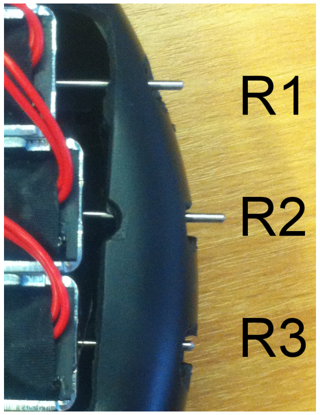

Figure 2: Enlarged right side of the steering wheel. R1 and R2 are activated and are pushing out. R3 is not active.

Introduction

In-car interactive systems can negatively impact safety if they increase mental workload or distract the driver [14]. Parts of the human body shifting out of the natural driving position in order to reach dials, knobs, etc. is referred to as biomechanical interference [20] which decreases the driver's ability to operate car controls such as change gears with the shifter. Thus, any hands-off-the-wheel task such as operating dials, eating, drinking etc. poses a safety risk [20]. Accordingly, an in-car interactive system should try to minimise eyes-off-the-road time as well as physical demands on the driver.

Wickens' Multiple Resource Theory [23] proposes the distribution of secondary task demands to regions in the brain that are unoccupied. Since driving is a highly visual task, and the auditory channel is often occupied by radio, conversations, navigation system, external noises etc., it seems reasonable to distribute some information to the haptic channel.

According to multiple resource theory [23], using the tactile channel might enlarge the total amount of information processed [22]. There are various motivating reasons for using tactile feedback in driving situations. Ho et al. have shown that spatially corresponding tactile (and audio) cues are helpful in maintaining good reaction times under high mental workloads [16]. According to Chapman et al. [6], kinaesthetic information about target location does not decay after 10 seconds, whereas visual information decays much more rapidly. Combining haptic location information with visual information can enhance target location memory [15]. Therefore, we chose to use tactile patterns on the steering wheel to give feedback to drivers.

A user study was conducted to investigate the effectiveness of different haptic patterns. These patterns were presented on the outer rim of the steering wheel using three solenoids under each palm. The measured data were analysed to identify characteristics of well perceivable patterns. A relationship between number of active solenoids and pattern identification accuracy was established.

Related Literature

Since the human hands are associated with high tactile acuity [17], we studied haptic feedback from the steering wheel. There already exists a rich body of research ranging from pneumatic balloons inflating underneath the driver's palm [8], force (torque) feedback [3] and vibratory [18] feedback on the steering wheel as warning signals.

Enriquez et al. [8] proposed warning signals via pneumatic balloons on the steering wheel which inflated underneath the driver's hand. Their approach had limitations: the pneumatic balloons were 10 cm long and thus provided only binary warnings.

As observed by Beruscha et al. [3], force (torque) feedback can remain unnoticed since it can be mistaken for driving related ("natural") torque caused by the road or the tyres.

A navigation task with six embedded vibration motors in the outer rim of the steering wheel was presented in [18]. The authors showed that in lab-controlled conditions participants could not tell where the vibration was coming from on the steering wheel and thus got confused about the direction presented.

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 showed promise but had limitations. It only facilitated the navigational driving task, no additional information was displayed.

Haptic feedback on the steering wheel has the potential to be an additional output modality. However, little is known about the efficiency and perceivability of tactile patterns presented in our proposed way, particularly when driving.

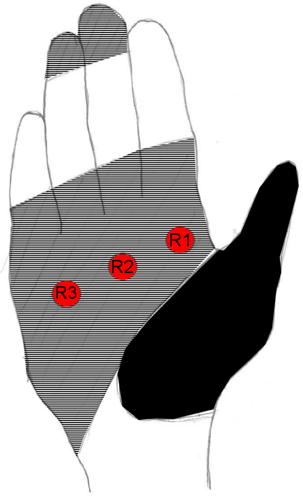

Figure 3: Inner right hand with its most sensitive regions to pressure input via a $1cm^2$ round metal pin. Black: thenar/thumb region; Gray/striped: median palmar region is 10-20% less sensitive than thenar/thumb region; White: fingers are more than 20% less sensitive to pressure input than thenar/thumb region [10]. The dots indicate where the solenoids were placed.

Perception of Haptic Patterns Through the Palm

In this section tactile properties of the human hand, specifically the advantages of the palm are listed. When gripping a cylindrical object the palm attributes to push force, the fingers contribute to gripping action [1]. It is important to notice that providing push feedback to the finger tips might loosen the grip and result in loss of control. Fransson and Hall showed that primarily the thenar and the median palmar region are receptive to pressure stimuli [10] (see Fig. 3). The study in [1] showed for all subjects and cylindrical objects, there is definite contact between palmar region and the gripped object. Thus push feedback from the steering wheel should aim at this area to guarantee skin contact. Gallace et al. [12] showed that up to four vibrotactile stimuli presented simultaneously resulted in nearly errorless identification. If the number of stimuli exceeds four, active counting starts, which is slow, error prone and attentionally demanding [11]. We assumed the neural mechanisms are the same for tactile pressure input and limited the number of active actuators to four.

Pressure input as a medium of tactile feedback on the skin creates indentations. To excite appropriate sensory units on the palm, the optimal skin indentation should range between 2 - 5 mm [19]. 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 [5] since subtlety in haptic icons causes increased pattern discrimination errors [13]. The minimum threshold of perceivable pressure is 0.2 N [6, 15]. Given a pin of 1.75 mm, 3.2 N is the pain threshold [4].

Equipment

A dynamically changing surface was created by embedding six solenoids[1] into a mock steering wheel (see Fig. 1). The solenoid pins were covered with a latex sheet. Given six solenoids, with a binary state (in/out), 64 feedback patterns are possible. However, patterns with five or more active solenoids were taken out as a result of recommendations by Gallace et al. [12], resulting in 57 patterns to test. According to Fransson and Winkel [9], 79mm and 90mm are the average hand breadths for females and males respectively. The physical layout of the solenoids allowed a minimum distance of 17.6 mm from pin to pin. To ensure perception by both genders, a maximum of three pins per palm could be implemented. The solenoid pins in this set up were 1.5 mm wide and they reached a maximum of 2.9 N (DC) at 100% duty cycle. The prototype haptic steering wheel was securely attached on top of a Logitech G27 racing wheel so that participants could steer the virtual vehicle during a simulated driving task (OpenDS[2]).

Experiment

The aim of this study is to investigate effective haptic feedback patterns the driver can perceive on a steering wheel in a simulated driving environment. The tactile patterns were presented on the steering wheel which the participant was asked to hold throughout the experiment. The driving task involved keeping a car in the middle lane of a five lane highway in the simulator. There were no other cars in the simulation. During the experiment, the randomly ordered 57 patterns were presented twice to each participant. In each trial, the participant held the steering wheel and awaited the cued stimulus. Once the haptic sensation was felt — which lasted for 3 seconds (as a result of max. 4 solenoids

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[1] http://uk.rs-online.com/web/p/dc-d-frame-solenoid/2501280/ Accessed 23.09.2015

[2] http://www.opends.de/ Accessed 11.01.2015

No of Pins	Overall
0	100.0%
1	86.2%
2	70.6%
3	47.9%
4	32.0%
total	54.6%

Table 1: Identification rate of different numbers of pins that are active simultaneously across all participants.

No of Pins	Overall
≤ 1	88.2%
≤ 2	78.8%
≤ 3	62.7%
≤ 4	54.6%

Table 2: Overall accuracy of patterns given different numbers of pins involved.

and 500-800 ms to shift attention) — the participant indicated what pattern was felt by checking the check box next to its associated actuator on the feedback screen. The simulation was paused whenever participants' feedback was requested. At the end, participants provided feedback about our system on a Likert scale: whether it was pleasant, distracting, useful and if they felt the were given enough time to perceive the patterns. Finally, participants discussed characteristics of the perceived patterns.

There was one experimental condition with varying tactile patterns (the number and permutation of energised solenoids). The tested patterns are listed in Table 3. Zero pins being active was one possible pattern. The purpose of this pattern was to determine whether participants felt phantom tactile sensations when there was no haptic feedback. The patterns had the following characteristics: number of actuated pins, number of hands involved in a pattern, whether it is horizontally mirrored across both hands (e.g. L1-R1, L2-R2, L3-R3), and whether the pins were adjacent to each other and perceived as one.

The independent variable was: haptic patterns. The dependent variable was accuracy: if *all* the pins for each pattern was selected correctly. Otherwise, the trial was counted as incorrect.

Twenty participants were recruited from our institute to take part in the study (10 male, 10 female) with an average age of 22.9 years (min=18, max=32) and an average of 4.37 years of driving experience (min=0.5, max=14). The experiment lasted 90 minutes and each participant was paid £10.

Results

The accuracy data were not parametric since the participants either correctly or incorrectly identified the presented patterns. Table 3 shows which patterns were identified correctly on average showing the mean accuracy (%) for each pattern. Patterns with one or two pins were perceived most accurately, with generally one pin on each hand. The more pins were involved in a pattern the less accurate was the identification. Thus, an analysis into the differences of the patterns was conducted: effect of number of pins on correct identification rate, most and least perceivable pins, number of hands involved in a pattern, and whether horizontally mirroring the pattern across both hands or adjacency of pins had an effect on accuracy.

Pattern	%	Pattern	%	Pattern	%
000000	100.0	000011	60.0	010110	42.5
000100	92.5	110000	57.5	001110	42.5
100000	90.0	111000	57.5	011001	42.5
001000	87.2	110010	57.5	010011	41.0
100100	85.0	000111	57.5	011010	40.0
010000	82.5	011000	56.4	111010	40.0
000010	82.5	001010	55.0	111100	35.0
010010	82.5	100011	53.8	111001	35.0
000110	82.5	110110	52.5	100111	35.0
000001	82.5	110001	52.5	110011	32.5
001100	80.0	110100	50.0	011110	30.8
100010	80.0	101101	50.0	011100	30.0
010100	75.0	001011	50.0	110101	30.0
100001	75.0	101001	48.7	001111	30.0
000101	75.0	100101	47.5	011101	27.5
001001	67.5	010101	47.5	011011	27.5
010001	65.0	001101	46.2	010111	27.5
101000	62.5	100110	45.0	101110	21.1
101010	62.5	101100	42.5	101011	20.0

Table 3: All the test tactile patterns and identification accuracy. The 0 and 1s for each pattern represent (from left to right): L1|L2|L3|R1|R2|R3.

	Score
Pleasant	2.75
Distracting	2.75
Useful	2.85
Time	4.25

Table 5: Questionnaire mean scores over all participants using the Likert scale with 1 “not at all” and 5 “very”. “Time” means if the participant felt s/he had sufficient time to identify the pattern presented.

Overall accuracy of identifying the correct pattern is at 54.6% (see Table 1). The participants perceived zero pins with 100% accuracy thus no phantom stimulus was felt when zero pins were presented. Taking out the patterns consisting of four pins increased the overall accuracy from 54.6% to 62.7% (see Table 2). Taking out three pin patterns further increases overall accuracy from 62.7% to 78.8% (see Table 2). Thus, the number of presented pins influences the performance significantly ($\chi^2(4, N = 2271) = 329.196, p < 0.0001$) (see Tables 1 and 2).

Determining which pin affects accuracy the most, a Friedman test was conducted. There is a significant difference between the perception of the individual pins ($\chi^2(1, N = 2271) = 261.347, p < 0.0005$). Chi-square tests revealed the percentages of error rates (100% - accuracy) for each pin individually (see Table 4) (the sum of all the errors is higher than 100% because multiple pins can be active simultaneously).

Pin	Error	Pin	Error
L1	13.1%	R1	14.2%
L2	21.3%	R2	13.6%
L3	27.7%	R3	19.2%

Table 4: Percentage of error rate for each pin, e.g. 19.2% of all R3 pins were perceived incorrectly.

Combination of active pins (i.e. the patterns) had different influence in overall performance. A Chi-square test was calculated comparing the error rates of mirrored and not mirrored patterns. A significant interaction was found ($\chi^2(1, N = 1674) = 60.784, p < 0.0005$) with 66.4% of presented mirrored patterns resulted in correct identification, compared to 53.0% of not mirrored patterns. Due to our design mirrored patterns included two and four pin patterns only. 68% of the not mirrored two pin patterns were correctly identified, whereas 78.3% of the mirrored two pin patterns were correctly identified ($\chi^2(1, N = 599) = 4.305, p < 0.023$). 29.1% of not mirrored four pin patterns resulted in correct identification, and 43.3% of the mirrored four pin patterns ($\chi^2(1, N = 597) = 8.877, p < 0.002$).

Analysis of number of hands involved showed that error rates across the hands were similar (41.1% left, 40.0% right, $\chi^2(1, N = 2271) = 15.133, p < 0.0005$). However, 49.2% of the patterns presented to both hands result in errors (due to design choices four pin patterns are always presented to both hands thus were excluded from this analysis).

Comparison of pattern identification of adjacent pins and not adjacent pins on each hand showed that perception is increased given adjacent pins (left: 48.3%, right: 48.3%) over not adjacent pins (left: 43%, right: 45.2%) ($\chi^2(, N =) =, p < 0.0005$).

Analysis of our questionnaire (see Table 5) shows that participants subjectively noticed the same issues revealed in our analysis. The bottom pins are deemed as more distracting than any other pin by 4/20 participants. In 6/20 answers it was stated that not mirrored patterns were mentally more demanding. In general, patterns with only one pin or all three pins on one hand were considered as least distracting, as well as symmetrical patterns. Patterns in which pins were adjacent to each other (e.g. R1-R2 or R2-R3, etc.) were harder to distinguish and caused less confidence in performance in 15/20 participants.

Discussion

The technology illustrated in the haptic steering wheel allows the user to process 57 different tactile stimuli via three solenoids embedded into the steering wheel under each palm. The results have shown, that participants have not missed a single tactile message. However, patterns consisting four pins being active at once caused high error rates (68%). Thus, the number of actuated solenoids influences pattern identification rate significantly. This is in accordance with the findings made in [11] where it is suggested to limit the number of tactile actuators to three. Analysis of up to three pins in a pattern showed an increase in overall accuracy from 54.6% to 62.7%.

Furthermore, the tactile pattern should be limited to one hand to avoid potential masking and response competition of two simultaneous stimuli [7]. Our results support these findings with 49.2% of patterns presented to both hands resulted in identification errors, compared to 41.1% (left) and 40.0% (right) of patterns presented to one hand. However, if a single pattern is separated onto both hands, both parts of the pattern should be mirrored, otherwise identification rate drops rapidly (66.4% vs 53.0%). Subjective feedback supports this (6/20 participants).

Physical layout of the solenoids influenced perception significantly. Most perceivable pins were L1, R1 and R2. 14/20 participants found the L1 and R1 as best perceivable pins. The pins L3 and R3 caused significantly more identification errors on each hand than the other pins. This was also noticed by 8/20 participants. This was due to the layout of our presented design which prohibited haptic feedback to the thumb region. Positioning the L3 and R3 pins in the thumb region can improve perception — even with four pin patterns — since this region is associated with most sensitivity to pressure input [10]. Pins presented to the right hand had slightly higher recognition rates than those to the left hand. We restrained from analysing the effects of handedness on the recognition accuracy of the individual pins, since only 2/20 participants were left handed in our study. One can assume the results are due to right handed participants being more, however, according to Hage et al. [21] there are no differences in tactile pressure perception between dominant and non-dominant hands.

Participants also mentioned a struggle to localise adjacent pins correctly. This is in accordance with our findings, adjacent pin patterns had a significantly worse identification rate (left: 48.3%, right: 48.3%) than not adjacent pin patterns (left: 43%, right: 45.2%).

Further analysis of our questionnaire showed that participants found pins were not “forceful” or “sharp” enough (6/20 participants). In order to avoid pain, the solenoid pins only created 2.9 N (DC) at 100% duty cycle. Furthermore, they were covered in a latex sheet which might have decreased the impact force. Other suggestions by participants were to space the pins out (4/20 participants). Two participants suggested to leave the middle pins R2 and L2 out, since less pins overall is preferred by 5/20 participants.

Conclusion and Outlook

Our study shows that tactile patterns, which are constructed using a maximum of three pins, can be conveyed to the user with high accuracy. Haptic feedback in cars can be used in an eyes-free context reducing visual loads on the driver. Creating patterns on the steering wheel could become a much more important market than just providing navigational information. We can envisage single actuator patterns being used for time-critical messages (dead angles and crossing pedestrians), and multiple actuator patterns for more complex and non-time critical messages (upcoming traffic conditions, road surface conditions, driving performance, etc.).

Future Work

In future work we will analyse car driving data from this study, e.g. lane deviation after a pin has been presented. Finally, in-car vibrations caused when driving on public roads might mask the pin array solution proposed in this paper. An investigation into this is planned.

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