Dynamic Cutaneous Push Messages from the Steering Wheel

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***Abstract*— In-vehicle systems, such as infotainment, can divert visual attention away from the road which may affect driving ability and safety. Tactile notifications from the steering wheel have the potential to decrease this distraction by reducing cognitive and visual demands. This paper presents an investigation into the efficacy of novel *Dynamic* Cutaneous Push (DCP) patterns, and their impact on driving performance. Six solenoids were embedded along the rim of the steering wheel, creating three bumps under each palm. In a simulated driving study, twenty DCP patterns were tested.Results showed pattern identification rates of up to 73.5% (circular motion presented to one hand). DCP notifications did not impact driving behaviour nor workload and showed very high user acceptance. DCP patterns have the potential to make driving safer by providing non-visual, highly directional, and instantaneous messages, for example to indicate an approaching cyclist or obstacle.**

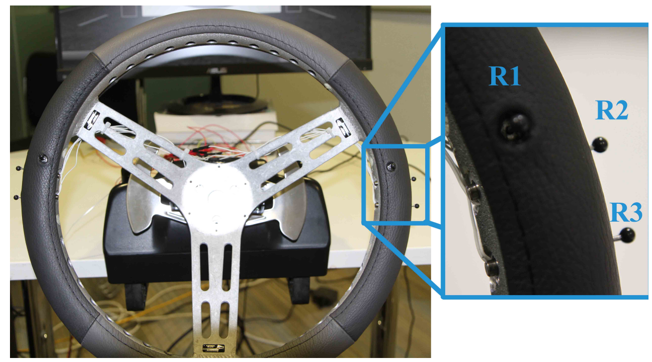

Fig. 1. Left: The Dynamic Cutaneous Push (DCP) steering wheel with six solenoids embedded into the rim (three on each side). Right: Close-up of the activated pins on the right side. DCP patterns presented to the palms result in high recognition accuracy without negative impact on workload nor degradation in driving performance.

I. INTRODUCTION

Large screens are becoming common in car cockpits. These may create more opportunities for visual distraction and could lead to drivers disengaging from driving [1]. The US National Highway Traffic Safety Administration ranked visual distractions (e.g. looking towards the centre console or handheld devices) as a greater threat to safety than purely cognitive distractions (e.g. talking, listening to music), with 30% of crashes [2] caused by visual distraction.

Research has shown that tactile feedback can reduce visual distraction from the infotainment system by using a non-visual channel for information presentation [3]. In contrast to auditory feedback, tactile notifications do not interrupt conversations or listening to music, and are a discreet message delivery system. Ho *et al.* [4] have shown that tactile cues capture a driver's attention quickly and accurately, demonstrating potential for robust message delivery without additional cognitive demand, nor impact on driving performance. The palms of the hands are the obvious location for tactile message display because they have the highest tactile acuity after the face, and they are in contact with the steering wheel while driving. Tactile notifications to the hands allow the driver to adhere to the "eyes on the road, hands on the wheel" [5] paradigm for safe driving. Our work investigates *Dynamic* Cutaneous Push (DCP) notifications from the steering wheel to the driver's palms, providing non-visual, instantaneous, spatialised, rich messages intended to allow drivers to keep their eyes on the road.

Other researchers have explored the use of tactile steering wheels for feedback and infotainment notifications. Solutions range from vibrotactile [6] and force-feedback [7], to moving surfaces under the driver's palms to hint the steering direction [8]. While previous tactile steering wheels can display rich [6], instantaneous [7] or spatial [9] information, Cutaneous Push messages can deliver all three.

Shakeri *et al.* [10] were the first to investigate Cutaneous Push from the steering wheel to the driver's palms. They embedded six solenoids into the rim of the wheel, three under each palm. They showed that Cutaneous Push messages had high recognition rates of 84.83% without a negative impact on workload or driving performance. However, they tested temporally *static* patterns: the number and positions of protruding pins did not change during feedback presentation, reducing the number of distinct patterns that could be created. Research has shown that presentation of *dynamic* spatiotemporal tactile patterns — such as pushing out one pin after another — result in higher recognition rates and quicker response times [11], as well as significantly reducing task workload [12]. Dynamic spatiotemporal notifications have been shown to exceed the performance of only spatially encoded patterns [13] because the limitations of spatial patterns can be overcome by applying time as another dimension to the stimulus. Dynamic patterns, in general, can offer a much richer stimulus set [13] as they allow users to interpret the tactile messages with familiar touch metaphors [12]. Well designed, dynamic tactile messages could be a powerful tool for fast and accurate tactile pattern recognition in vehicles.

This paper presents a first study to investigate novel *Dynamic* Cutaneous Push technology on the steering wheel. Twenty different dynamic patterns were tested in a simulated driving study to measure their impact on user workload, driving performance, recognition rate, and preference. Our

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initial results show that DCP patterns can be delivered reliably to the driver without negatively impacting driving or mental workload. This work's contributions are: 1) a first exploration of Dynamic Cutaneous Push patterns from the steering wheel; 2) an assessment of the impact DCP patterns have on workload and driving behaviour; and 3) an extension of the current Cutaneous Push vocabulary through the introduction of *dynamic* notifications. DCP patterns can improve driver safety by presenting information effectively to the tactile channel, freeing up visual resources for driving-related information.

II. RELATED WORK

Research has investigated several ways of using dynamic haptic feedback to present information to drivers. The two main advantages of presenting dynamic spatiotemporal patterns are that: a) they can create tactile illusions [14] which allow for fast and straightforward recognition of patterns [11], [6]; and b) they offer a much richer stimulus set when constrained to a fixed time window compared to static patterns [13]. In this section, we discuss several approaches and reflect on what characteristics make for effective information presentation from the steering wheel.

Most research has focused on vibrotactile stimuli since they provide instantaneous and familiar feedback to the driver. Dynamic spatiotemporal vibrotactile notifications, often called Tactons [15], have been presented to the driver by embedding vibrotactors into the steering wheel [11], into the driver's seat [16], by attaching them to the seat belt [17] or onto the driver's body [18]. Morrell *et al.* [16] used spatiotemporally dynamic vibrotactile notifications to inform the driver about cars in the blind spot. They embedded a 3 x 5 matrix of tactors into the driver's seat, each column representing a motorway lane (five lane scenario). The number of tactors increased with decreasing distance of the approaching vehicle. They showed that driver awareness was improved and a reduction in the time the car spent in the host vehicle's blind spot was achieved. Meng *et al.* [18] attached vibrotactors on the driver's wrist and torso and showed that spatial and temporal dynamic patterns can significantly enhance information processing in driving situations compared to static patterns. Dynamic stimuli can produce tactile illusions such as impressions of *approach* which evoke faster reaction times and recognition of notifications [4].

Others have investigated spatiotemporal dynamic patterns to create tactile illusions of *movement* along the steering wheel. Hwang *et al.* [11] embedded 32 vibrotactors into the steering wheel to investigate pattern recognition performance. They found that dynamic patterns increased recognition rates and response times compared to static patterns. Kim *et al.* [6] embedded 20 vibrotactors into the steering wheel and activated them in either clockwise or anti-clockwise patterns. They too report high pattern recognition rates and significant improvements in driving performance when vibrotactile feedback was provided dynamically. The benefit of dynamic tactile patterns is that they have a greater information bandwidth than static ones, without increasing complexity [13].

The literature discussed so far used vibrotactors to create dynamic tactile notifications. However, research has shown that vibrotactile notifications on the steering wheel can be mistaken for natural in-car vibrations [19] which reduces their robustness for message delivery. Further, even in laboratory conditions, participants struggle to correctly identify the location of the vibration on the wheel [19], especially when tasked with simulated driving [7]. This is because the vibrations easily spread around the wheel, due to its stiff structure. Yet, spatial tactile cues successfully direct a driver's visual attention to time-critical events [4]. Cutaneous Push [10] is an alternative solution which can deliver tactile messages with spatial information instantaneously to the driver's palms via an actuated surface (Fig 1). As the sensory units in the palm are very sensitive to mechanical transients such as skin stretches (e.g. taps with finger or pen) [20], *Static* Cutaneous Push (SCP) has been used successfully to convey tactile messages to the driver [9], [21] via six solenoids inside the steering wheel rim which can be actuated independently. However, SCP pattern identification accuracy dropped significantly with increasing number of actuators (i.e. three solenoids or more per pattern); and display duration for high pattern recognition rates last up to 2000 ms, which slowed down interaction. In this paper, we investigate whether *dynamic* spatiotemporal patterns created by a Cutaneous Push steering wheel allow for high recognition of tactile notifications without negatively impacting the driving task or mental workload.

III. EXPERIMENT

A simulated driving study was designed to investigate the effectiveness of DCP feedback from the steering wheel. The key aim was to gain insight into the characteristics of patterns which provide the most effective feedback and distract the driver least from the primary driving task.

The same steering wheel design was used (Figure 1) as presented in [10], [21], as well as the same study setup as [10], which allowed for some general comparison of results. The DCP patterns on the wheel were created by embedding six solenoids into a pre-drilled metal steering wheel.

A. Pattern Design

Twenty dynamic patterns were created, grouped into 7 Families. Two examples of dynamic feedback patterns will be described in detail: sequential arrow to the left and clockwise circular motion. These two are representative of their Family and encompass most features present in other Families. For the sequential arrow to the left pattern, pins L2, L1, R1, R2 protrude from the steering wheel rim one after the other. Total duration of pattern presentation was 1 second, each pin was displayed for 250 ms.

Clockwise circular feedback is presented to both hands with pins L1, L2, L3, R3, R2, and R1 protruding sequentially one after the other. Total pattern presentation duration was 1 second, each pin was actuated for 167 ms (1000 ms / 6 pins). Each pin retracted before the protrusion of the next was initiated. Table I shows all 20 dynamic motions that were presented to participants. For purposes of simplified discussion and analysis, the dynamic feedback motions were further classified into seven *Families* (Table I).

The duration of each feedback pattern was limited to either 500 ms or 1000 ms because findings by Hwang *et al.* [11] suggest a presentation of maximally three stimuli per 500 ms. Animation for dynamic patterns in Table I, Families 1, 3, 4, 6, and 7 lasted for 500 ms; and 1000 ms (i.e. 2 *x* 500 ms) for circular motions presented sequentially to both hands, Family 2; sequential arrow motions lasted for 1000 ms, Family 5.

B. Hypotheses

Hypotheses were informed by a pilot study, results from Shakeri *et al.* [10] on static Cutaneous Push feedback, and Hwang *et al.'s* [11] results on tactile illusions from the steering wheel.

- **H1** Recognition rate will differ between the different types of feedback patterns;
- **H2** Dynamic Cutaneous Push patterns will not increase lane deviation;
- **H3** Dynamic Cutaneous Push patterns will not increase workload.

H1 anticipates a difference in recognition accuracy for the seven Families of motion. A pilot study indicated that circular motions presented to one hand and presented sequentially may have highest perception performance. Based on findings from [10], mirrored patterns such as in Table I Family 4 are expected to result in high correct identification because redundantly displayed information confirms perception [19]. Similar to SCP feedback [10], **H2** does not predict an impact of the feedback on driving performance and **H3** does not predict any effects of the feedback on user workload.

C. Measures

The Independent Variable was: DCP feedback pattern. The Dependent Variables were: pattern recognition accuracy (if the motion for each dynamic pattern was selected correctly; otherwise, the trial was counted as incorrect), locus recognition accuracy (if a pattern was displayed to either right/left palm and was identified correctly; otherwise the trial was counted as incorrect), lane deviation (metres), and perceived workload (NASA TLX). Additionally, demographics, and open questions regarding preferences and potential application areas for DCP messages were captured with a questionnaire at the end of the experiment.

D. Procedure

Upon arrival, participants were briefed about the study and given an introductory training session. During this, participants were shown the feedback patterns and instructed on how to classify the perceived pattern according to the scheme above (Table I). Following this, participants were provided with a single driving block where each pattern was presented randomly (Balanced Latin Square order). After each presentation, they were asked to classify the pattern according to the table of patterns (Table I).

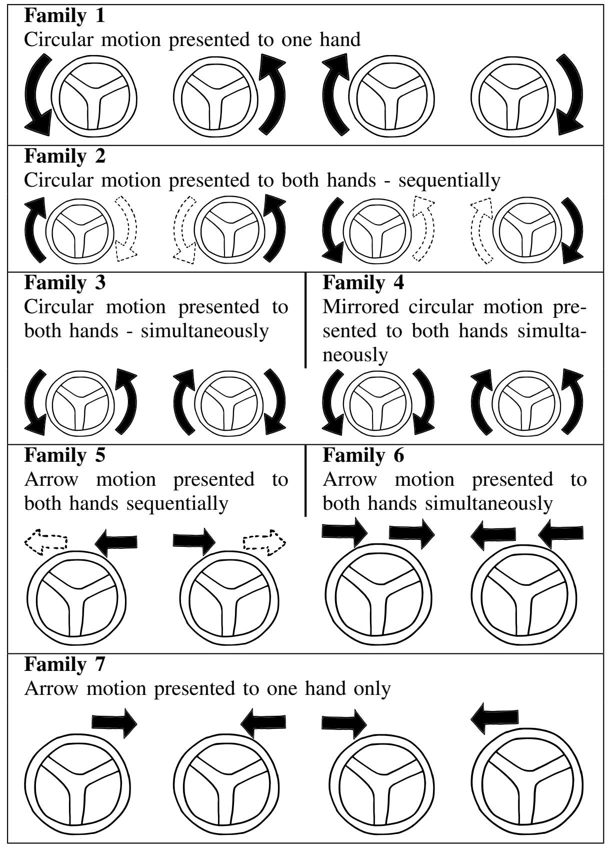

TABLE I
Seven Families of Dynamic Cutaneous Push notifications. Black arrow: presented first (or simultaneously); dotted arrow: presented second.

The main experiment was designed exactly like the initial training. However, it consisted of 4 blocks, with each block presenting all 20 patterns in a random order. A single trial consisted of a) 6 seconds of driving (i.e. the *before* interval), b) 500 or 1000 ms of pattern presentation (*during*), c) 5-7 seconds of post-pattern-presentation driving (i.e. *after* interval), and d) a break where pattern classification was conducted. During pattern classification, participants used the mouse provided to click the image of the pattern that represented the perceived motion (Table I). The *before* and *after* pattern presentation periods allowed the driver to regain stabilised driving and the measurement of the impact of the feedback on driving behaviour.

E. Participants

Twelve participants (six female) aged between 19 and 36 years (μ=24.4, σ=5.3) were recruited via our university's online forum. They all held a valid driving license with 0.25 to 18 years of driving experience (μ=4.7, σ=5.0). One participant reported to be left handed.

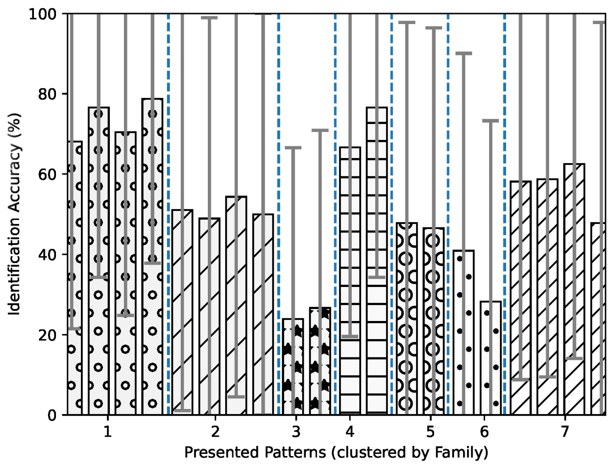

Fig. 2. Individual pattern identification accuracy, clustered by Family (Table I) via hash patterns and dashed vertical line.

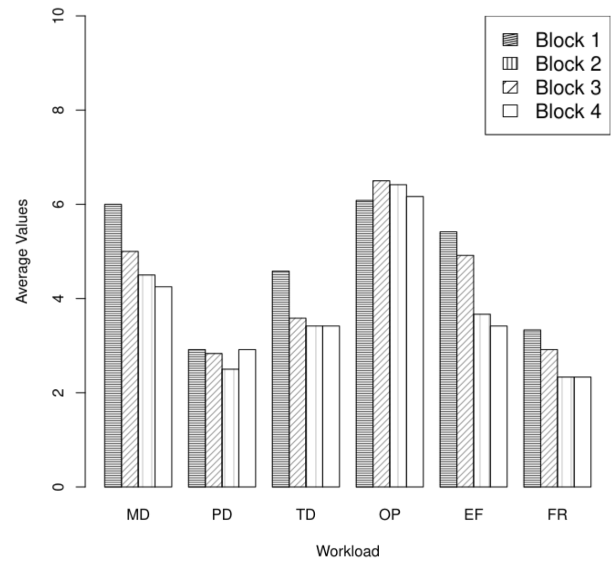

Fig. 3. Average results of the NASA TLX questionnaire. MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, PE: Performance, EF: Effort, FR: Frustration.

IV. RESULTS

A. Recognition

Overall recognition performance was 51.46%, with highest performance in the circular motion to one hand pattern at 73.51% and lowest in the circular motion presented to both hands simultaneously at 25.27%. An Analysis of Variance (ANOVA) on a binomial regression model found a significant main effect of pattern Family on recognition performance: $chi^2(7) = 2.934, p = 0.003$. *Post hoc* Tukey tests revealed that circular motion to one hand and circular mirrored patterns had significantly higher recognition rates than the other Families ($z = 2.934, p = 0.003$). The location of the DCP feedback was correctly identified with 93.48% accuracy (e.g. patterns presented to the left palm only: Family 1, patterns 1 and 3, and Family 7, patterns 3 and 4). An ANOVA on a binomial regression model found a significant main effect of individual pattern on recognition performance: $chi^2(19) = -3.798, p <= 0.0001$ (Figure 2). *Post hoc* Tukey tests revealed that patterns 2 ($z = 5.015, p = 0.001$), 3 ($z = 4.624, p = 0.001$) & 4 ($z = 5.229, p = 0.001$) from Family 1, and pattern 2 from Family 4 ($z = 5.015, p = 0.001$) had significantly higher recognition rates than other patterns.

B. Lane Deviation

Driving performance was measured via deviation from the optimal driving path; the centre of the middle lane was considered as zero lane deviation. It was measured through the root mean square error (RMSE) of the vehicle's lane position with respect to the lane centre. Driving data were non-normally distributed for *before* ($W = 0.849, p - value < 0.001$), *during* ($W = 0.860, p <= 0.001$), and *after* ($W = 0.863, p <= 0.001$) driving intervals — as shown by Shapiro-Wilk normality tests. A multivariate analysis of variance (MANOVA) was conducted to test whether DCP Family impacted lane deviation (*before* ($F(1,3) = 0.051, p = 0.821$), *during* ($F(1,3) = 0.152, p = 0.697$), and *after* ($F(1,3) = 0.006, p = 0.936$)). There was no statistically significant effect of DCP Family on lane deviation.

C. Subjective Data

On a scale from 1 to 5 with 5 being ”agree strongly”, users rated the pleasantness of the feedback with a mean of 3.5, the distraction caused with 2.8, and usefulness with 3.9.

A MANOVA test showed there was a significant impact of learning on perceived workload ($\chi^2(1) = 4.933, p = 0.031$), with the last block of the study resulting in the lowest workload ($\chi^{(}1) = 7.347, p = 0.009$). The more experience users gained with the DCP cues, the less mentally and temporally demanding they perceived the feedback, as well as experiencing less effort and frustration.

V. DISCUSSION

For in-car feedback to be successful, it needs to support interaction while not having a negative impact on the driver's workload and control of the vehicle. This study showed that DCP notifications such as circular clockwise to one hand (73.51% recognition accuracy) and mirrored to both hands (71.91%) were an effective way of delivering messages to the driver, for example from the infotainment system.

> **H1** Recognition rate will differ between the different types of feedback patterns

Overall DCP pattern recognition performance was at 51.46%. There were significant differences in pattern recognition accuracy between the Families; **H1** was therefore accepted. For instance, circular patterns presented to one hand (Family 1) resulted in recognition accuracy as high as 73.86%, whereas circular patterns presented simultaneously to both hands (Family 3) resulted in 25.27% accuracy. The highest performing DCP cues were patterns 1 (76.59%) & 2 (78.72%) from Family 1, and pattern 2 from Family 4 (76.59%). DCP stimuli presented simultaneously to both hands (Family 3) were poorly recognised, due to the hands masking each other. Participant P6 commented that "simultaneous rotation and simultaneous left to right/right to left" were the most distracting patterns. However, if the patterns were mirrored across two hands (Family 4), perception was good (71.91%); redundant presentation of information to both hands improved recognition performance.

The average for arrow motion (Families 5 - 7) recognition was 51.42%. Interestingly, patterns consisting of two stimuli (such as single arrow patterns; Family 7) were perceived as "too fast" by participants, while three stimulus patterns (Family 1) were described as "perfect, no need to change" (P3). The *perceptual space-time distortion* [14] phenomenon may explain how the presentation of three stimuli within 500 ms was not described as too fast but the display of two stimuli was, even though two stimulus patterns had more display time (each 250 ms) compared to three stimulus patterns (each 167 ms). Goldreich [14] explained that short stimuli displayed in rapid succession onto one body site (e.g. left arm) perceptually "expand" the time elapsed between consecutive events and "reduce" the distance between stimulus origins. This can be explained with following two assumptions: 1) if stimuli are placed close to each other, and displayed in short intervals, the stimuli can be perceived as if they originate from the same source; and 2) objects which contact the skin tend to move slowly. The second assumption is very important to understand as it might explain the poor arrow pattern recognition observed in this study. Because objects which contact the skin are assumed to be slow, two temporally close taps on the skin might have been interpreted as originating from the same source; that is, "the object that tapped me is still in the same place". However, three quick taps along the skin are against the expectation that the object is slow, therefore the velocity perception of the object is reconciled with the expectation; that is, the object and its taps along the skin are not perceived as quickly as they actually were. The *perceptual space-time distortion* phenomenon explains how two tap patterns (single hand arrows; Family 7) are perceived as too fast, as well as their poor perception accuracy.

Interestingly, sequential arrows (Family 5) had lower recognition accuracy than single hand arrows (Family 7). The overall longer display duration of 1000 ms did not support recognition. The *perceptual space-time distortion* might have acted doubly. Two perceptual distortions took place, one on each hand; instead of two arrow motions per hand supporting each others' perception. Participant P12 emphasised that "the single-hand patterns were amazing, I could definitely perceive them with little mental effort and they felt natural as well".

A key difference between our study and the previous Cutaneous Push research was that feedback display duration was reduced to 500 ms (max 1000 ms) compared to Shakeri *et al.*'s 2000 ms duration for each static pattern. This change was motivated to reduce interaction duration, because long interaction can increase workload [22]. Our findings show that three pin patterns, as in Family 1, and even six pin patterns, as in Family 4, can result in high recognition performance given a display time of 500 ms. Not only is DCP display duration quartered compared to previous static cutaneous push research [10], but the recognition rate of patterns from Families 1, 2, and 4 are similar compared to static patterns consisting of 3 or more pins.

> **H2** Dynamic Cutaneous Push patterns will not increase lane deviation
>
> **H3** Dynamic Cutaneous Push patterns will not increase workload

No impact of DCP was observed on either driving performance or workload. Analysis of the NASA TLX data showed that over time, participants experienced significantly less mental demand, effort and frustration with the feedback technique. **H2** and **H3** were accepted. Our findings further suggest that DCP patterns result in higher perceived performance, lower frustration, and lower effort than SCP, supporting the literature regarding reduced workload in dynamic spatiotemporal tactile patterns recognition compared to static ones.

It is important to assess user preference and satisfaction because it plays a key role in the acceptance and adoption of technology, especially in driving situations where the assessment of subjective impressions indicate whether drivers are likely to use a system [23]. In questionnaire responses, participants were positive about DCP notifications. Participant P2 said "I would rank this [technique] very highly and [as] very useful". Three participants (P5, P7, P12) mentioned that they felt "safe" due to the limited distraction DCP caused from the main driving task. Participant P5 anecdotally compared DCP with vibration from the steering wheel: "I think its a good method of feedback, vibration would be slightly stressful to some users". To investigate this further, a future study should perform an assessment of Cutaneous Push in terms of urgency, valence/arousal, and message content, comparing the results to vibrotactile steering wheel feedback.

Participants' positive attitudes towards DCP led to descriptions of practical applications. P3 proposed that DCP messages could be used to warn the driver about sleepiness and drowsiness as "it somehow gives me a sensation to keep focused". Other suggestions were to use DCP as navigational assistance (P1), about hazards and speed cameras (P2), and "[DCP] could be used to draw my focus to the gauge cluster" (P6). Participants mainly appropriated DCP patterns from Families 1, 2, and 4 for their use cases, which correlate with high pattern recognition rates (Figure 2). The main commonality between these Families is a display of 3 stimuli per 500 ms (or mirrored in the same direction). The positive engagement with the technique shows promise and suggests drivers' willingness to use DCP in cars.

Further investigation of DCP notifications is valuable because they can deliver rich tactile messages immediately and discretely to the driver, with a high localisation accuracy. From a practical perspective, these characteristics are necessary for various critical and non-critical messages such as from the infotainment system, upcoming traffic alerts, road surface conditions, driving performance, etc., as spatial information successfully directs a driver's visual attention to time-critical events [4], and tactile notifications from the steering wheel reduce drivers' reaction times to the event [24]. DCP on the steering wheel opens up new design possibilities for such in-car feedback through the salient nature of the stimuli. As participants suggested the feedback was suitable for notifications, specific DCP patterns could present information effectively to the tactile channel (e.g. "destination reached" (P4), "turn right" (P10)), while freeing up the visual resources for driving-related information. For example, we envision a driver slowing down to make a right turn but not noticing a cyclist in the bicycle lane, approaching from behind. A DCP cue with circular motion presented anti-clockwise (i.e. Table I, Family 1) to the right palm could signal to the driver that the cyclist is approaching on the right, and shorter pauses between the patterns as the cyclist draws closer, indicating that they should not turn. In future applications, DCP could also be implemented into other surfaces in addition to the steering wheel, such as the arm rest, window frame and the door handle. For example, if the driver rests a hand on the arm rest, DCP cues could inform them about the remaining fuel level.

SCP feedback has already found application in driving research and was shown to be successful for providing turn notifications for in-car navigation systems [9] and for feedback on mid-air gestures [21]. Using DCP cues can provide even richer feedback, widening possible application scenarios. We plan to explore the design of DCP feedback forapplications, such as providing drivers with situational awareness which require highly spatial and immediate feedback [8], for which DCP cues are ideally suited.

VI. Conclusions

This paper presents a first exploration of novel *Dynamic* Cutaneous Push feedback patterns displayed on the steering wheel, and an assessment of their recognition rates, impact on driving performance and perceived user workload. Our findings suggest that DCP feedback can be an effective display method in cars, conveying accurate and highly localised dynamic haptic patterns without impacting driving performance nor cognitive demand. The positive user feedback shows great promise for driver acceptance and adoption of DCP notifications. In addition, as information is presented non-visually, DCP notifications can make driving safer by allowing drivers to keep their eyes on the road. We propose the following initial design recommendations for successful Dynamic Cutaneous Push messages: 1) Present patterns to a single hand for high recognition accuracy; 2) If presented to both hands, then the patterns should be mirrored in the same direction; 3) Given a 500 ms display time, a notification should consist of three tactile points per pattern.

In conclusion, Dynamic Cutaneous Push feedback cues offer designers an effective new way of presenting information to the driver in a safe and accurate way on the steering wheel.

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