This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

HapWheel: In-Car Infotainment System Feedback Using Haptic and Hovering Techniques

Filipe Quintal, *Universidade da Madeira, LARSyS-ITI,* Marco Lima, *Universidade da Madeira, Faculdade das Ciências Exatas e Engenharia*

***Abstract*—In-car devices are growing both in complexity and capacity, integrating functionalities that used to be divided among other controls in the vehicles. These systems appear increasingly in the form of touchscreens as a cost-saving measure. Screens lack the physicality of traditional buttons or switches, requiring drivers to look away from the road to operate them. This paper presents the design, implementation, and two studies that evaluated HapWheel, a system that provides the driver with haptic feedback in the steering wheel while interacting with an Infotainment System. Results show that the proposed system reduced both the duration of and the number of times a driver looked away from the road. HapWheel was also successful at reducing the number of mistakes during the interaction.**

***Index Terms*—Touchscreen, Automotive, Haptic feedback, Infotainment**

I. INTRODUCTION

MOST modern vehicles incorporate some type of infotainment system (IS), which usually aggregates entertainment equipment, such as the radio, with information delivery to the driver, like the navigation system [1]. It is estimated in 2020, 80% of new vehicles were sold standard with some type of IS [2]. The industry is converging into the integration of all the functionalities mentioned above in a single touchscreen at the center console of the vehicle. An anecdotal example is the Tesla Model 3 or X, which integrates all but the steering, turn indicators, and brake and accelerate controls in the so-called infotainment systems. This decision allows greater flexibility in the interaction since the controls do not need to be fixed in place, and they can be adapted to different interaction contexts. Other benefits of this trend include lower cost of manufacturing and maintenance [2], and the possibility to easily update the system [3]. However, this trend is not immune to to scrutiny. The interaction with the IS is mainly a visual task. Therefore, it is possible to interfere with the driving effort, which is predominantly (95%) a visual task [4], thus increasing the probability of an accident. Studies have shown that drivers who perform other visual tasks while driving have a three times greater risk of accidents than drivers who do not [5]. Furthermore, research focused on studying the risk of using IS while driving found that these systems are the leading cause of visual distraction [6], [7], probably, since when a driver operates the IS, 70% of the time is spent looking away from the road [8]. This paper reports on the design and evaluation of HapWheel, a system that combines work from multi-modal interaction for touchscreens in vehicular applications, with solutions that delivered feedback in the steering wheel of the vehicle. The end goal of the proposed system is to reduce driver's distractions while operating the IS. In the remaining document, we first present the related work that influenced our approach. The next following present the proposed system. Subsequently, we report the results of a pilot and user study. To conclude the document we discuss the results, and present our conclusions as well as prospects of future work.

II. RELATED WORK

Researchers were quick to draw a parallelism between the interaction with an IS screen and smartphone or tablet, consequently drawing inspiration from those fields. Therefore, one of the most explored approaches was to rely on multi-modal interfaces with an haptic component in the IS screen [8]–[13]. Other approaches focused on the design of the IS interface to facilitate in-vehicle interaction (e.g [14], [15]), which could for example predict the driver's input [16], or adapt the IS interface to the driver's intent [17]. The unique vehicle setting also provided opportunities for feedback, such as feedback in the steering wheel [18]–[20] or seat-belt [20]. Moreover considering strategies unique for vehicular applications, researchers have experimented with various ways of providing haptic feedback on the steering wheel. Examples include conveying directional information from the navigation system [18], and several types of warnings to the driver [20] such as forward collision, lane change or lane departure [21]–[23]. There is also a considerable body of work regarding how to build the feedback in the vehicle. Sungjae Hwang and Jung-hee Ryu developed a prototype [18] where 32 haptic actuators were mounted around the steering wheel to provide information such as ”turn left”, ”turn right”, or ”alert”. Ploch et al. [19], developed a prototype where the steering wheel had a mobile surface, allowing it to rotate freely from the wheel itself, while providing haptic feedback via the stretched skin of palms. Chun et al. [20] proposed a system that employs six vibration motors placed on the upper part of the wheel, allowing them to be activated to alert the driver about the presence of other vehicles at the driver's blind spot. An alternative design was proposed by [24] which used solenoids embedded on the rim of the wheel, the system was capable of depicting 57 different patterns. A user study disclosed that participants could successfully detect the elicited pattern 54.6% of the time.

A. Simulating Physical Controls

Pitts et al. [9] disclosed that drivers prefer short a singular feedback (resembling a ”click”) in the IS. The authors also

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

reported that in a simulated environment, drivers performed better when interacting with the IS with visual, sound, and haptic feedback. The condition with only visual feedback resulted in worst driver satisfaction and performance. Grane and Bengtsson [10] also studied this approach , with a test of different interaction techniques while driving. The system included a rotary device capable of depicting haptic patterns, and it was used to perform the selection in the IS. The authors revealed that a combination of visual and haptic strategies did not negatively affect the driving performance when compared with driving with no distractions. A concurrent approach is to convey the location or appearance of virtual elements in a touchscreen. El-Glaly et al. [25] proposed a touchscreen interface with tactile elements to aid the interaction with visually impaired individuals. Similarly, Pielot et al. [26] leveraged the natural border of a touchscreen, together with vibrotactile feedback to guide visually impaired individuals when interacting with an MP3 player. Corsten et al. [27] used tactile ”landmarks” placed at the back of a touchscreen in order to enable eyes-free interaction with the device. Zimmermann et al. [28] implemented a low-cost solution with silicon foil attached to a simulated IS. The added haptic guidance resulted in a lower interaction time when comparing with tapping the screen. Similarly, Rümelin and Butz [14], reveal that a small fixed physical knob on the touchscreen allowed visually impaired individuals to interact with the IS. It even performed favorably when comparing with an identical IS with no tactile queues but bigger buttons.

B. Interacting with the IS

Researchers have studied various techniques to improve interaction with the IS. González et al. explored an approach that did not require the driver to remove their hands from the steering wheel, and the interaction was done with the thumb through a touch-sensitive surface on the wheel [29]. The results showed that users preferred the proposed approach instead of interacting directly with the screen. Other authors have explored ways of adapting the IS interface to facilitate the interaction without distractions, for example, by expanding the interaction target [30]. Pfleging et al. mounted a screen on the steering wheel and made common controls (side mirrors and windows) accessible through gestures and voice commands. Compared to a traditional physical interface, the authors found that task performance (e.g., time to adjust the side mirrors) was negatively affected, although driving performance remained the same. Other authors explored techniques which implemented indirect interaction with the IS, where the driver can point at the screen and interact with it without touching it. Ahmad et al. [16] developed a predictive system, using a motion controller that detects which item the user will select early in the pointing gesture. The study determined that the time to select a target was reduced by 39% compared to traditional touchscreens.

C. Opportunities for feedback

Henderson et al. [31] studied how to leverage the feedback in the users' non-dominant hand instead of delivering it in the interaction location. Their work revealed comparable results between the two conditions. One can hypothesize that Henderson's work could provide an opportunity for steering wheel haptic or vibrotactile feedback during the interaction with IS. Taking into account current hand placement recommendations, which state that drivers must place their hands at 3 and 9 o'clock on the steering wheel [32]. And also considering studies which found that the palm region between the thumb and the fingers' base is ideal for sensing haptic feedback, especially while holding cylindrical objects, as is the case of a steering wheel [24], [33]. We can argue that haptic feedback in a steering wheel should be rendered at the 9 o'clock position of the wheel (for left-hand drive vehicles) since that is the location with the highest probability of the feedback being acknowledged.

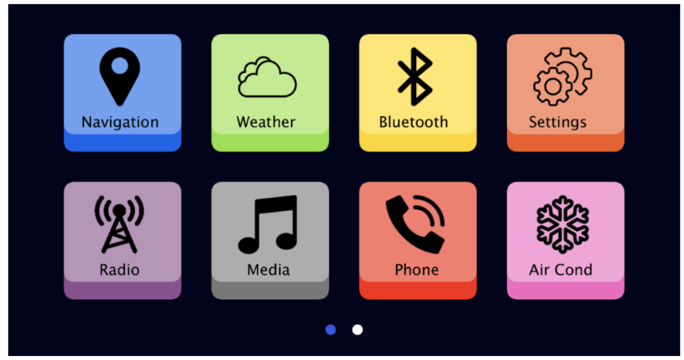

Fig. 1. Simulated infotainment system used in the user study.

III. HapWheel System

Considering the body of work presented above, we propose the HapWheel system (see Figure 2). In this system, we combine the contributions regarding interface design and visual/haptic feedback for IS, our end goal is to combine these approaches to reduce driver's distractions when interacting with the IS. The HapWheel deploys an array of 9 haptic actuators in the steering wheel of a vehicle, which work together with the IS to aid the interaction with the system while driving a vehicle. The system also adopts a Leap Motion Controller to infer the driver's right-hand position before interacting with the IS.

A. Infotainment

The feedback apparatus in the steering wheel is complemented by a simulated IS. The system was developed in Processing[1] and mimics a common infotainment system. To assure familiarity with the device, the design was inspired mainly by the IS present in the 2019 Renault Clio[2], the best selling car at the time of designing this system at the location where the system was tested and one of the all-time best-selling cars in Europe. The system contains big colorful icons for the most common commands in IS, such as Radio, Navigation, Phone, or Air Conditioning (see Figure 1).

[1]https://processing.org/
[2]https://group.renault.com/news-onair/actualites/nouvelle-clio-les-defis-de-lombre-releves-par-les-ingenieurs-de-developpement/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

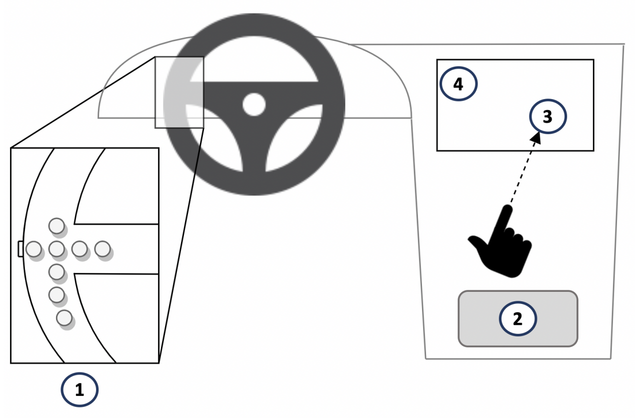

Fig. 2. Setup of the components used in the users study with HapWheel. 1-Actuators in the steering wheel; 2-LeapMotion sensor; 3-Pointing position translated to the IS screen; 4-Simulated IS screen.

B. Haptic Feedback Component

The haptic actuators are positioned in a cross pattern and placed at the 9 o'clock position of the wheel for left-hand drive cars (see Figure 3 left , and Figure 2 number 1), so that the feedback is provided in the palm of the left hand while the interaction with the IS happens with the right hand (see Figure 2), as recommended in the reviewed work [24], [32], [33]. The system uses Eccentric Rotating Mass actuators, paired with a DRV2605L driver. The positioning of the actuators was chosen according to the assumption that when the driver is interacting with the IS, they will not remove the left hand from the wheel, and also from the assumption that during that interaction, the driver will not be performing maneuvers (e.g., cornering). The haptic actuators are used to provide feedback on the selection of any command like presented by Pitts, et al. [8] (note that in this study [8] , the feedback was provided directly on the touchscreen, while our approach provides the feedback on the steering wheel).

C. Conveying Physical Controls

As stated above, the haptic actuators allude to the interface elements' position and relay positional information to the user through haptic feedback. This is done by providing feedback in the form of a directional pattern, vibrating the actuators sequentially. HapWheel supports four patterns (swipe right, left, up, down) by activating the actuators sequentially in the X and Y axis (see Figure 4 number 2). When the user's finger hovers inwards/outwards through the edge of a virtual button, vibrations reproduce a swipe pattern (in the steering wheel) according to the position of the right hand (see Figure 4). For example, if the driver approaches a button from the left border inwards, the swipe right is reproduced by the actuators, as presented in Figure 3 right. Each swipe pattern has a duration of 350ms. The selection of any item in the interface is still accomplished by physically touching the screen. This approach attempts to reassemble the tactile elements in touchscreens found effective in the reviewed work [14], [26], [28]. We believe this direction can be helpful when the virtual controls are large or there are a small number of elements on the screen simultaneously (for example, in the main screen of the IS). Furthermore, the driver also gets feedback assuring them that they actually pressed a control through a "click" pattern, which was proven effective in the aforementioned study by Pitts, et al. [8]. In this pattern, all the actuators are collectively activated for a period of 75 ms. In some situations the proposed swipe patterns might not be suitable. For example, when entering the destination in the navigation system, a on-screen keyboard is presented, and even a small movement leads to the user's finger hovering through several keys at once. If a swipe pattern was played every time the participant hovered a key, the resulting vibrations playing one after another could be very tough to understand. In those cases, the system provides a shorter and "click" feedback when the user's finger crosses the edge of a control. To assure a user would not confuse this "click" vibration with the feedback used to confirm a selection, a stronger "click" was used to confirm a selection, and a shorter smoother "click" was used when swiping the finger over the on-screen keyboard.

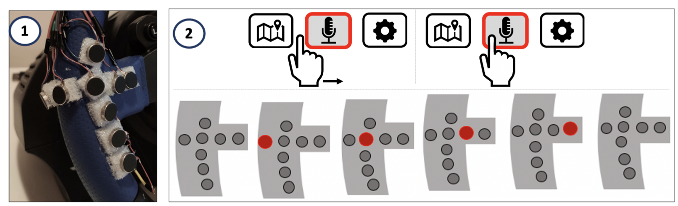

Fig. 3. 1-Actuators placed at the steering wheel. 2-Haptic actuators' sequence as the user hovers a button left to right. The red border represents the actuator active at each moment. In this example, the actuation "moves" from left to right as the user enters a control from the left border inwards.

D. Hover Pointing Component

For the interaction with the IS, a Leap Motion Controller[3] is placed below the IS touchscreen to track the user's right hand and translate the pointing of the index finger to a position on the screen (in a similar setup as Shakeri et al. [34]). The position is calculated in real-time to minimize lag and provide feedback on the steering wheel as instantly as possible, since studies have shown that delaying the feedback increases the total time of eye glances off the road [11]. The projected screen position is filtered to eliminate noise in the movement and in the hand motion detection data. The data was sampled at 60Hz, and filtered with a moving average algorithm that accounts for the last 20 data points.

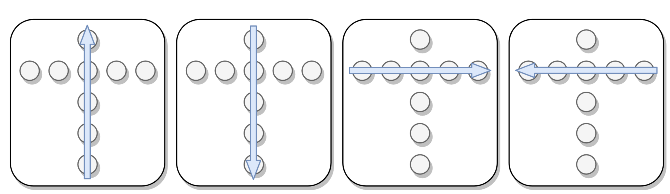

Fig. 4. Activation sequence followed by the actuators to portray the swipe up, down, right and left patterns.

[3]https://www.ultraleap.com/product/leap-motion-controller/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

TABLE I
SIX QUESTIONS PART OF THE NASA TLX QUESTIONNAIRE

Metric	Question	Minimum Value	Maximum Value
Mental Demand	How mentally demanding was the task?	Very Low	Very High
Physical Demand	How physically demanding was the task?	Very Low	Very High
Temporal Demand	How hurried or rushed was the pace of the task?	Very Low	Very High
Performance	How successful were you in accomplishing what you were asked to do?	Perfect	Failure
Effort	How hard did you have to work to accomplish your level of performance?	Very Low	Very High
Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?	Very Low	Very High

E. Setup

The system setup is divided into two main modules developed in Python: The interaction and the feedback modules. The interaction module runs on a computer. It is responsible for presenting the simulated IS in an external touchscreen, tracking the user's hand and gaze direction, and calculating the actuation patterns sent to the feedback module. The feedback module is responsible for activating the actuators according to the received pattern, and this module runs in a Raspberry Pi 3B+ micro-computer connected to 2 TCA9548A multiplexers linked to 9 Addafruit™ Vibrating Mini Motor Disc haptic drivers.

The communication is unidirectional from the Interaction to the Feedback module. It was implemented using a socket. A new pattern is sent as soon as it is identified in the Interaction module.

F. Evaluation

A pilot and a user study were carried out to evaluate the HapWheel system. The pilot evaluated users' capacity to differentiate directional information conveyed by haptic actuators in a steering wheel, and a study assessed the complete HapWheel system in a simulated driving scenario. It was decided to separate the system evaluation into these two instances to assess haptic feedback in a controlled scenario. Given the complexity of the setup, the pilot study provided a strong foundation for the final evaluation. We believe this approach minimized the risk of possible shortcomings in the haptic feedback component affecting the complete system evaluation.

IV. PILOT STUDY

For this pilot study, 13 participants were recruited. Participants were aged between 20 and 38 years old (M = 24.6, SD = 4.96, 9F). Only one participant did not have a driving license. The pilot was carried out in a quiet room with no distractions. Only the participant and researcher responsible for the evaluation were present. On average, each test lasted approximately 12 minutes. Although the actuators emit a small buzzing sound during actuation, it is important to clarify that it was almost imperceptible. Consequently, we argue, this sound could not be used to reliably guess the pattern. The pilot evaluation respected the following protocol:

1) Introduction, where demographic data was collected, followed by an explanation of the prototype and its purpose;
2) Training, where the participant was shown how to grip the steering wheel and how each pattern felt. Then the participant could test any pattern for as long as they needed up to a point where they comfortable that they could easily identify each one;
3) The test, where an automated program played 11 series of 20 patterns, each in a randomized order (the first series was discarded as training, for a total of 200 patterns recorded per participant). Ten seconds were granted after each series to rest or adjust the grip;
4) After each pattern, the user had 3 seconds to record their answer. This answer was the participant's best guess for the rendered pattern. It was recorded using a keyboard directional keys. The up key was used to indicate a swipe up answer, the left key for the swipe left, the down key for a swipe down, and the right key for the swipe right pattern. No visual interfaces were used. At this stage, the interaction between the participant and the researcher was minimal, and the participant was completely focused on deciphering the played pattern;
5) Questionnaire, where the NASA TLX was employed to assess the participant's perceived workload for this task. This questionnaire is composed of six questions to be answered on a scale from a low to a high value (see Table I for details about the metrics, questions, and minimum/maximum values in the NASA TLX questionnaire). This scale is divided into 20 increments, each one with a value of 5 for a total of 100;
6) Final interview, where each participant could provide feedback and suggestions.

A. Pilot Results

In general participants in the pilot study were successful at correctly identifying the haptic feedback in the steering wheel, resulting in an average success rate of 95.3% (*SD* = 6.43%) when considering all participants and possible patterns. Looking individually at each pattern, there was no significant difference between patterns, as confirmed by a Kruskal-Wallis test ($H(3)$ = 2.41, p = 0.49). All the patterns had a high detection success rate. On average, participants succeeded in guessing the swipe up pattern for 97.0% of the attempts (*N* = 650, *SD* = 3.9%), swipe down for 96.3% (*SD* = 5.8%), swipe right for 93.8% (*SD* = 6.5%) and swipe left for 94% (*SD* = 9.1%). Table II summarizes all the provided and detected stimulus during the pilot, organized by pattern. Regarding the post-study NASA TLX questionnaire, we computed the results following the questionnaire authors' instructions [35] without weighting the individual questions. Participants in the pilot study averaged an absolute score of 18.43 (*SD* = 8.32) out of 100 (less is better). The perceived frustration

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

TABLE II
COUNT OF THE PROVIDED STIMULUS VERSUS THE RECOGNIZED STIMULUS DURING THE PILOT

Provided stimulus	Recognized stimulus: Swipe Up	Swipe Down	Swipe Left	Swipe Right
Swipe up	631	2	11	6
Swipe Down	2	625	6	16
Swipe Right	8	25	7	610
Swipe Left	28	2	611	9

averaged a final score of 7.5 (*SD* = 5.95). This indicates that using the haptic component, as implemented in this prototype, does not represent a high subjective workload. Finally, the post-study interview disclosed that, in general, participants found the tasks simple and easy to perform. Participants also mentioned that it was quite effortless to detect the patterns, this observation, corroborates the results from the NASA TLX presented above. No other particular recommendations or concerns were raised.

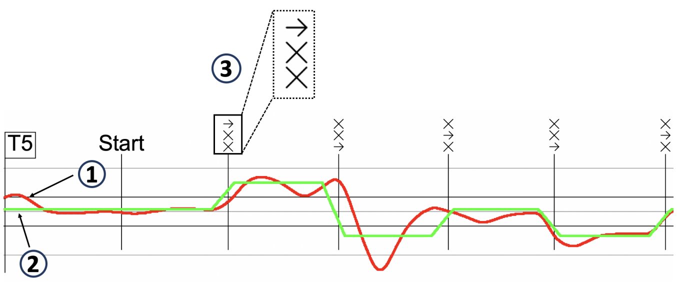

Fig. 5. Graphical example of the output from the Lane Change Test. 1- The red line represents the path followed during the test. 2- The green line represents an ideal path. 3- Signs which informs the participant/driver to change lane, in this example, the sign directs the driver to the left-most lane.

V. USER STUDY

A user study was planned to evaluate the proposed system in a simulated driving scenario. Due to the ongoing pandemic, the study was conducted in person in a region without positive covid-19 cases for more than 14 consecutive days. All the appropriate sanitation measures were strictly followed. The study structure followed a setup similar to what is found in the reviewed work (e.g., [10], [29]), employing a gaming steering wheel and pedals, the HapWheel system, and a driving simulator running in a computer, Figure 2 and 7 shows the study setup. The selected driving simulator was proposed by [36]. This software implements the ISO Lane Change Test standard [37], which aims at assessing the demand of secondary tasks while driving. These secondary tasks could occur from different sources, such as handling feedback from the radio, phone, other drivers, or the IS. This approach has been widely followed in the reviewed work [9], [10], [12], [38], [39], since it provides a inexpensive and standardized way of assessing the drivers attention. The test consists of a simulation of a 3 lane road. This road has 18 pairs of different signs placed on each side of the road at fixed intervals, instructing the driver to change the lane (see Figure 5). The test returns the average *deviation*, in meters, between an ideal path and the path followed by a participant when changing its lane (see Figure 5). The used implementation for the Lane Change Test allows randomizing the lane change instructions and their order. The test input could be a keyboard, however studies have shown better results when using a steering wheel, and pedals [40]. Figure 7 portrays a participant performing the user study with HapWheel.

A. Methodology

The study followed a within-subjects design. Nine participants carried on 3 tasks in the HapWheel system: Selecting a radio station; Navigating the main menu; Inputting an address in the Navigation. Each of these tasks were performed twice, firstly without haptic feedback in the steering wheel (*no-feedback* condition), and then with haptic feedback (*feedback* condition). For the main menu and radio tasks, the researcher responsible for the evaluation would indicate a new radio station or menu item to be selected with 5 seconds of interval between interactions, for a total of 20 selections per trial. For the navigation task, participants were asked to input an address in the system using the on-screen keyboard, and an auto-complete feature was available after entering the fifth character. The tasks were selected based on research conducted on the most popular features of an IS [41], and the tasks finalized when the driver navigates back to the main screen of the IS. Our methodology also employed eye-tracking software to measure the number of times the driver looked away from the road, and the duration spent for each time looking away. Participants age range from 20 to 48 (*M*=31.66, *SD*=11.18, 3F). Four participants drove more than 4 times a week, four drove at least once a week, and one drove at least once a month. The study protocol consisted of the following steps:

1) Introduction to the study;
2) Familiarization with the HapWheel system and the simulator (exploring the simulated IS, driving in the Lane Change Test test with the gaming wheel and pedals until the participant felt comfortable with the system);
3) Calibration of the eye-tracking software;
4) Lane Change Test without interacting with the IS, which was the *base-case* of the study;
5) Lane Change Test while interacting with the radio without haptic feedback;
6) Lane Change Test while interacting with the radio with haptic feedback;
7) Lane Change Test while navigating the menu without haptic feedback;
8) Lane Change Test while navigating the menu with haptic feedback;
9) Lane Change Test while selecting a destination in the Navigation without haptic feedback;
10) Lane Change Test while selecting a destination in the Navigation with haptic feedback;
11) NASA TLX questionnaire (repeated after steps 6,7,8,9, and 10). The process lasted between 30 and 40 minutes.

Apart from the *deviation* returned from the Lane Change Test, the number of times the driver took their eyes from the road (glances, *g*), and the time spent looking away from

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

the road (glance time, *gt*) were also recorded. The researcher responsible for conducting the test also annotated each time a participant made a mistake in the IS, for example, selecting the wrong control (miss-clicks, *c*).

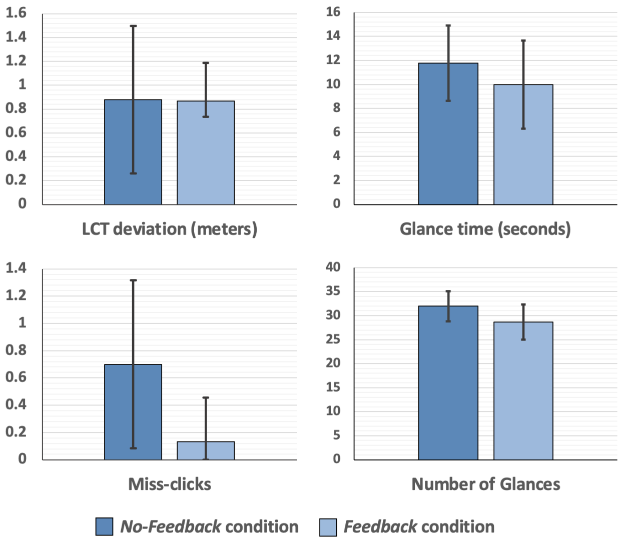

Fig. 6. Graphical representation of the *miss-clicks, deviation, glance time* and *glances* dependent variables, for the Feedback and No-Feedback conditions.

Fig. 7. Participant performing the driving simulation during the study.

B. User Study - Results

This section presents the collected data from the pilot and user study. All the statistical tests presented bellow were preceded by a normality fitting evaluation (Kolmogorov-Smirnov test), and the appropriate parametric or non-parametric test was carried out.

The first analysis aimed at simply confirming that interacting with the IS affects the driving behavior. For this the base-case (*B*) deviation (*d*) score was compared against the *d* for the feedback (*F*) and no-feedback (*N*) conditions. As expected participants average a lower *d* (0.521 m ,*SD*=0.228), for the *B* case when comparing with the *N* case (0.899 m, *SD*=0.462), and *F* case (0.894 m ,*SD*=0.456). An one-way repeated measures ANOVA test confirmed this observation (*F(3,9)* = 5.135, *p* = 0.018), which returned significant differences between the *B*, *F* and *N* cases. Pair-wise comparisons confirmed the difference between the *B* and *N* conditions (*t(9)*=-2.425, *p*=0.042), and between the *B* and *F* conditions (*t(9)*=-2.469, *p*=0.039), no significant difference was found between the *F* and *N* conditions (*t(9)*=-0.05, *p*=0.961).

TABLE III
MEANS(M) AND STANDARD DEVIATIONS(SD) VALUES FOR THE DEPENDENT VARIABLES MEASURED DURING THE *N* AND *F* CONDITIONS

	No-Feedback		Feedback	
	M	SD	M	SD
Glance time (s)	11.63	3.28	10.02	3.77
Number of Glances	31.11	7.93	27.30	6.47
Miss-clicks	0.66	0.64	0.14	0.333
Lane Change Test deviation (m)	0.88	0.46	0.89	0.45
Mental Demand	47.41	26.42	48.15	26.66
Physical Demand	35.93	18.37	35.74	19.19
Temporal Demand	39.82	24.36	40.74	23.26
Performance	38.33	31.44	44.26	35.95
Effort	45.04	30.03	45.59	29.34
Frustration	32.96	28.94	39.82	30.61

Afterwards, the analysis of the user study was focused on the deviation(*d*), glances(*g*), glance time(*gt*) and *miss-clicks*(*c*) dependent variables, and in the *F* and *N* cases . The data returned from each driving task was averaged per participant to dilute possible changes between tasks, (for example a participant could be already familiar with one of the tasks from their personal life), resulting in 9 values per variable per condition. Table III presents the average values for the collected dependent variables.

It is apparent that the *g, gt* and *c* averages were lower in the *F* condition. The impact of the *F* independent variable on the dependent variables stated above, was further analysed by four within-subjects t-tests. This analysis returned three significant differences between the *F* and *N* conditions, for *g* (*t(9)*=3.774, *p*=0.005), *gt* ((*t(9)*=3.514, *p*=0.008)), *c* (*t(9)*=-3.506,*p*=0.008) independent variables, and, like it was mentioned before, one not significant difference regarding the *d* dependent variable (*t(9)*=-0.050,*p*=0.961). Figure 6 presents an overview of the collected data regarding the *c*, *d*, *gt* and *g* variables.

Finally, the perceived workload of interacting with the IS, measured through the NASA TLX averaged 38.33 (*SD*=31.43) for the *N* and 44.35 (*SD* =35.95) for the *F* conditions respectively. A paired samples t-test did not found any significant difference between those two conditions (*t(9)*=-0.993, *p*=0.350). Analysing the different metrics collected through the NASA TLX in detail, a set of six within-subjects t-tests did not found any significant difference between the *B* and *F* conditions for the: *Mental Demand* (*t(9)*=-0.226, *p*=0.827), *Physical Demand* ((*t(9)*=0.189, *p*=0.855)), *Temporal Demand* (*t(9)*=-0.387,*p*=0.709), *Performance* (*t(9)*=-0.993,*p*=0.350), *Effort* (*t(9)*=2.306,*p*=0.866), *Frustration* (*t(9)*=-0.948,*p*=0.371) metrics.

Table III, presents the average and standard deviation for all the metrics collected through the NASA TLX. A graphical representation for these values is also presented at Figure 8.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

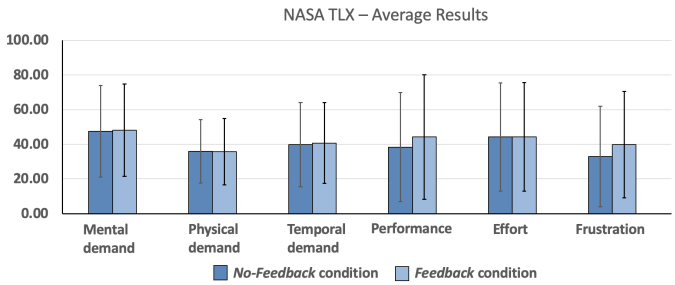

Fig. 8. Graphical representation of the average and standard deviation values for the metrics obtain through the NASA TLX questionnaire during the study.

VI. Discussion

A. Detecting directional information in the steering wheel

When compared to related work, the results from the pilot study show improvements over comparable implementations. Comparing with the prototype proposed at [18], our system was able to produce a similar or greater number of haptic patterns with a higher success rate (95.3% vs. 90.5%). Moreover, our pattern duration was shorter (350ms vs. 450ms), allowing us to present more patterns in a shorter time span, reducing the interaction time with the IS. Comparing our approach to [19], we note the same advantage of producing a greater number of different patterns. Furthermore, the steering wheel complexity is reduced by having no moving parts on the proposed approach, leading to a more robust and longer-lasting product. With these results, we can argue that the proposed system successfully presented four different patterns on a steering wheel. The pilot results provided a solid base for the interaction proposed by the HapWheel.

Even without relying on the hover pointing component tested in the study, the haptic component could be used as an independent system. It could be integrated with other tracking methods to solve problems associated with the current IS interaction. For example, our haptic system could be integrated with part of the solution proposed by Pitts et al. [8], where the user would slide their finger on the touch-screen while receiving the appropriate haptic feedback on the steering wheel, and, finally, press harder to select a target control.

B. Improving driving performance

The driving performance was measured by the deviation returned from the Lane Change Test. Our work confirmed the assumption that interacting with IS produces an extra cognitive load, leading to changes in the driving patterns compared to driving without distractions. This result is in line with the state of the art [42], and we believe confirms the relevance of work in this field. Nevertheless, the proposed system could not significantly improve the driving performance when interacting with the IS (when comparing to driving without haptic feedback in the *N* condition). This observation was also found at [9], [10]. Pitts et al. hypothesize that even though this result is against the consensus that multi-modal feedback improves performance, one should consider the singular characteristics of the driving interaction scenario. Moreover, although there are studies that indicate a significant or apparent benefit of using haptic or audio feedback in vehicular applications [12], [43], more research should be conducted in this field. We concur with Pitts's observations, furthermore, considering the difference in driving performance between the *F* and *N* condition, one can argue that the strongest factor influencing the driving performance is the interaction with the IS and not the type of feedback given by the IS. This type of assessment is, by definition, the purpose of the Lane Change Test, *assess in-vehicle secondary task demand*. Thus, one might conceive that the simplicity of this test, composed of a straight road with no traffic, and no pedestrians. Aimed at measuring horizontal deviations in the driving to evaluate in-vehicle secondary task demand, is not the most appropriate metric to assess smaller changes in the secondary tasks feedback.

C. Reducing driving distractions

As stated in the introductory sections, the proposed system main objective is to reduce driving distractions, which is one of the primary causes of road accidents [5]. The discussion of this aspect of the system is focused on the *F* and *N* conditions, since we assume, there were no distractions when participants performed the study completely focused in the road without interacting with the IS (in the *B* condition). While there were no significant differences in the *deviation* for the conditions mentioned above, there were significant differences for the *glances*, and, *glance-time* dependent variables favoring the *F* condition. We believe these are promising results for the proposed approach.

Driving is a much more complex task than portrayed in the Lane Change Test. Driving relies greatly on visual input, Shinar and Schieber [4] stated that driving is a 95% visual task. Therefore, reducing the time a driver spends looking away from the road can significantly impact safety. This assumption is backed by evidence that distractions while driving relate directly to issues such as pedestrian run over or crashes [44]. As mentioned before, most of the reviewed work did not account for the user's gaze during the evaluation. We did, however, find similarities between our results and [45], in which, through eye-tracking software, the authors found that touch interaction was the preferred technique. Porter et al. [46] also states that the inclusion of haptic feedback was successful at reducing the number of glances when driving. We believe our work builds on state of the art regarding haptic feedback in the IS, mainly towards delivering the feedback away from the interaction location.

D. Interacting with IS

When interacting with the IS in the *F* participants committed fewer errors. Furthermore, this task was not significantly more taxing than the *N* condition. Those observations are in line with the body of work on haptic feedback in a multi-modal interface for touch-screens [47], [48], and for touch-screens in vehicular applications [9], [10]. Our work presents novel results considering the haptic feedback position away from the interaction in the screen in a vehicular scenario. This experience was found in other scenarios such as touch-screens and wearable devices [31]. We believe that it provides more freedom for designers of car systems regarding the placement of the information, interaction, and feedback. While the pilot study showed that participants were successful at quickly detecting haptic patterns in the steering wheel, informal conversations with participants during the study revealed that the preferred feature was the ”click” confirmation of on-screen selections. This observation needs to be further scrutinized. However, we can find a resemblance with the encouraging results of on-screen haptic ”clicks” in both vehicular applications [8] and other types of touchscreens [31].

VII. Limitations

The design of the user study could be improved by changing the order of the driving tests. A 7x7 Latin Square Design would arguably increase the validity of the results. This issue is limited because the participants were familiar with HapWheel once the study started (see step 2 of the study methodology), yet we believe this is a possible drawback to the validity of the results. Another limitation of the HapWheel system is related to the position of the left hand of the driver. While recommendations advise drivers to drive with the hand positions at the 3 and 9 o'clock, it is not expected that the driver's hands remain in that position during a whole trip. This observation limits the ability of the feedback being delivered. An approach to address this limitation is to extend the actuation so that the feedback could be replicated at different locations in the steering wheel.

VIII. Conclusions

In this article, we presented HapWheel, a system that aims at reducing the attention needed to interact with modern IS. We propose a system that combines haptic feedback in the steering wheel with a hovering strategy to infer where the user is pointing. Delineating the interface edges through haptic patterns in the steering wheel and confirming actions (e.g., pressing a virtual control on the screen). A pilot study allowed us to assess participants' capacity to detect directional information through a set of haptic actuators in the steering wheel. The pilot study results paved a path to a user study with the full system, in a simulated IS, using the haptic and pointing component in a standardized simulated driving task. Comparing with a *N* condition, the proposed system successfully reduced the number of times a driver took their eyes away from the road and the duration of the period spent looking away from the road during the simulated driving test. Additionally, HapWheel reduced the number of mistakes when interacting with the IS. The extra cognitive load resulting from the haptic feedback was not classified as more demanding task.

We believe the interaction with the IS cannot be discussed without examining the IS in question. We designed a simulated IS that replicated as close as possible one of the most popular systems in the market. However, we argue that, like for any other computer system, the IS design will always be an important factor for all the dependent variables considered in this paper. Therefore, work in this field should not be carried out in a vacuum, this paper drew inspiration from work in haptic feedback, both in vehicular and non-vehicular applications. Similarly, designers from the industry and research field should also look into fields such as touch-screen interaction or critical system design when building IS systems. So many aspects of the design of a vehicle are mandated by law so that, certain safety or environmental standards are met. Perhaps aspects of the design, interaction, and performance over time (since performance degradation could be an issue in the long term) of an IS should also be subject to regulations, so an acceptable level of driver distraction is never surpassed in normal conditions.

IX. Future Work

During informal testing, we realized that the feedback swipe patterns were not suitable for controls such as address input on the on-screen keyboard. As future work, we believe it would be interesting to characterize which controls in the IS are suitable for the feedback proposed by HapWheel.

Another study that could help understand and discuss our results would request users to repeat the pilot procedure while performing the LCT driving test. This proposed study would assess the detection accuracy and deviation dependent variables in isolation. Most studies in the field do not execute a separate assessment for the feedback using the LCT driving test, without any other independent factor (e.g. [12]–[14], [34], [49], [50]). Nonetheless, we believe it would be a valuable addition to the field, and it would also strengthen our results.

Acknowledgments

This work was supported by the Portuguese Fundação para a Ciência e a Tecnologia under grants nºUID/EEA/50009/2019 and UIDB/50009/2020, and by the European Commission by the grant number 731249.

References

[1] G. Meixner, C. Häcker, B. Decker, S. Gerlach, A. Hess, K. Holl, A. Klaus, D. Lüddecke, D. Mauser, M. Orfgen, M. Poguntke, N. Walter, and R. Zhang, “Retrospective and future automotive infotainment systems 100 years of user interface evolution,” in *Automotive User Interfaces: Creating Interactive Experiences in the Car*, ser. Human–Computer Interaction Series, G. Meixner and C. Müller, Eds. Springer International Publishing, 2017, pp. 3–53.

[2] P. A. Consultants, “BearingPoint: 80% of new vehicles connected by 2020,” Aug. 2015. [Online]. Available: https://www.consultancy.uk/news/2353/bearingpoint-80-percent-of-new-vehicles-connected-by-2020

[3] M. Phelan, “Study: More cars will get automatic software updates,” 2016. [Online]. Available: https://www.usatoday.com/story/money/cars/2016/09/06/study-more-cars-get-automatic-software-updates/89899568/

[4] D. Shinar and F. Schieber, “Visual requirements for safety and mobility of older drivers,” *Human Factors: The Journal of Human Factors and Ergonomics Society*, vol. 33, pp. 507 – 519, 1991.

[5] S. G. Klauer, T. A. Dingus, V. L. Neale, J. Sudweeks, and D. J. Ramsey, “The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data,” 2006.

[6] M. A. Perez, “Safety implications of infotainment system use in naturalistic driving,” *Work (Reading, Mass.)*, vol. 41 Suppl 1, pp. 4200–4204, 2012.

[7] “Car Accidents Caused by In-vehicle Infotainment Systems Distraction,” May 2019. [Online]. Available: https://www.napolinlaw.com/orange/car-accidents/infotainment-systems-distraction/

[8] M. J. Pitts, G. Burnett, L. Skrypchuk, T. Wellings, A. Attridge, and M. A. Williams, “Visual–haptic feedback interaction in automotive touchscreens,” *Displays*, vol. 33, no. 1, pp. 7–16, Jan. 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0141938211000874

[9] M. J. Pitts, L. Skrypchuk, T. Wellings, A. Attridge, and M. A. Williams, “Evaluating User Response to In-Car Haptic Feedback Touchscreens Using the Lane Change Test,” 2012, publisher: Hindawi Limited. [Online]. Available: https://core.ac.uk/display/26945887

[10] C. Grane and P. Bengtsson, “Driving performance during visual and haptic menu selection with in-vehicle rotary device,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 18, pp. 123–135, May 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1369847813000077

[11] B. Chaparro and M. Deron, “How Important is Visual Feedback When Using a Touch Screen?” 2000.

[12] H. Richter, R. Ecker, C. Deisler, and A. Butz, “HapTouch and the 2+1 state model: potentials of haptic feedback on touch based in-vehicle information systems,” in *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’10. New York, NY, USA: Association for Computing Machinery, Nov. 2010, pp. 72–79. [Online]. Available: https://doi.org/10.1145/1969773.1969787

[13] A. Ng, S. A. Brewster, F. Beruscha, and W. Krautter, “An evaluation of input controls for in-car interactions,” in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, ser. CHI ’17. New York, NY, USA: Association for Computing Machinery, 2017, p. 2845–2852. [Online]. Available: https://doi.org/10.1145/3025453.3025736

[14] S. Rümelin and A. Butz, “How to make large touch screens usable while driving,” in *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’13. New York, NY, USA: Association for Computing Machinery, 2013, p. 48–55. [Online]. Available: https://doi.org/10.1145/2516540.2516557

[15] R. Ecker, V. Broy, K. Hertzschuch, and A. Butz, “Visual cues supporting direct touch gesture interaction with in-vehicle information systems,” in *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2010, pp. 80–87.

[16] B. I. Ahmad, P. M. Langdon, S. J. Godsill, R. Donkor, R. Wilde, and L. Skrypchuk, “You Do Not Have to Touch to Select: A Study on Predictive In-car Touchscreen with Mid-air Selection,” in *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. Automotive’UI 16. New York, NY, USA: ACM, 2016, pp. 113–120, event-place: Ann Arbor, MI, USA. [Online]. Available: http://doi.acm.org/10.1145/3003715.3005461

[17] P. Tchankue, J. Wesson, and D. Vogts, “The impact of an adaptive user interface on reducing driver distraction,” in *Proceedings of the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2011, pp. 87–94.

[18] S. Hwang and J.-h. Ryu, “The Haptic steering Wheel: Vibro-tactile based navigation for the driving environment,” *2010 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*, 2010.

[19] C. J. Ploch, J. H. Bae, W. Ju, and M. Cutkosky, “Haptic skin stretch on a steering wheel for displaying preview information in autonomous cars,” in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2016, pp. 60–65, iSSN: 2153-0866.

[20] J. Chun, I. Lee, G. Park, J. Seo, S. Choi, and S. H. Han, “Efficacy of haptic blind spot warnings applied through a steering wheel or a seatbelt,” vol. 21, pp. 231 – 241, 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1369847813000892

[21] C. Ho, N. Reed, and C. Spence, “Intuitive’vibrotactile collision warnings for drivers,” *Human factors issues in complex system performance*, pp. 169–176, 2007.

[22] J. Campbell, C. Richard, J. Brown, and M. McCallum, “Crash warning system interfaces: Human factors insights and lessons learned, final report,” *Seattle, WA: Battelle Center for Human Performance and Safety*, 2006.

[23] P. G. Griffiths and R. B. Gillespie, “Sharing control between humans and automation using haptic interface: primary and secondary task performance benefits,” *Human factors*, vol. 47, no. 3, pp. 574–590, 2005.

[24] G. Shakeri, S. A. Brewster, J. Williamson, and A. Ng, “Evaluating Haptic Feedback on a Steering Wheel in a Simulated Driving Scenario,” in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, ser. CHI EA ’16. New York, NY, USA: Association for Computing Machinery, May 2016, pp. 1744–1751. [Online]. Available: https://doi.org/10.1145/2851581.2892497

[25] Y. N. El-Glaly, F. Quek, T. Smith-Jackson, and G. Dhillon, “Touch-screens are not tangible: Fusing tangible interaction with touch glass in readers for the blind,” in *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, ser. TEI ’13. New York, NY, USA: Association for Computing Machinery, 2013, p. 245–253. [Online]. Available: https://doi.org/10.1145/2460625.2460665

[26] M. Pielot, A. Kazakova, T. Hesselmann, W. Heuten, and S. Boll, “Pocketmenu: non-visual menus for touch screen devices,” in *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, 2012, pp. 327–330.

[27] C. Corsten, C. Cherek, T. Karrer, and J. Borchers, “Hapticase: Back-of-device tactile landmarks for eyes-free absolute indirect touch,” in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, ser. CHI ’15. New York, NY, USA: Association for Computing Machinery, 2015, p. 2171–2180. [Online]. Available: https://doi.org/10.1145/2702123.2702277

[28] S. Zimmermann, S. Rümelin, and A. Butz, “I feel it in my fingers: Haptic guidance on touch surfaces,” in *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*, ser. TEI ’14. New York, NY, USA: Association for Computing Machinery, 2014, p. 9–12. [Online]. Available: https://doi.org/10.1145/2540930.2540938

[29] I. E. González, J. O. Wobbrock, D. H. Chau, A. Faulring, and B. A. Myers, “Eyes on the Road, Hands on the Wheel: Thumb-based Interaction Techniques for Input on Steering Wheels,” in *Proceedings of Graphics Interface 2007*, ser. GI ’07. New York, NY, USA: ACM, 2007, pp. 95–102, event-place: Montreal, Canada. [Online]. Available: http://doi.acm.org/10.1145/1268517.1268535

[30] I. Aslan, A. Krischkowsky, A. Meschtscherjakov, M. Wuchse, and M. Tscheligi, “A Leap for Touch: Proximity Sensitive Touch Targets in Cars,” in *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’15. New York, NY, USA: ACM, 2015, pp. 39–46, event-place: Nottingham, United Kingdom. [Online]. Available: http://doi.acm.org/10.1145/2799250.2799273

[31] J. Henderson, J. Avery, L. Grisoni, and E. Lank, “Leveraging distal vibrotactile feedback for target acquisition,” in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, ser. CHI ’19. New York, NY, USA: Association for Computing Machinery, 2019, p. 1–11. [Online]. Available: https://doi.org/10.1145/3290605.3300715

[32] A. Zakhareuski, “10 and 2 Driving No More? How to Hold Steering Wheel Correctly,” 2019. [Online]. Available: http://driving-tests.org/beginner-drivers/how-to-hold-a-steering-wheel/

[33] Y. Aldien, D. Welcome, S. Rakheja, R. Dong, and P. E. Boileau, “Contact pressure distribution at hand–handle interface: role of hand forces and handle size,” *International Journal of Industrial Ergonomics*, vol. 35, no. 3, pp. 267–286, Mar. 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0169814104001623

[34] G. Shakeri, J. H. Williamson, and S. Brewster, “Novel multimodal feedback techniques for in-car mid-air gesture interaction,” in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’17. New York, NY, USA: Association for Computing Machinery, 2017, p. 84–93. [Online]. Available: https://doi.org/10.1145/3122986.3123011

[35] S. G. Hart, “Nasa task load index (tlx). volume 1.0; paper and pencil package,” 1986.

[36] S. Mattes, “The lane change task as a tool for driver distraction evaluation. ihra-its workshop on driving simulator scenarios, october 2003-dearborn, michigan. wwwnrd. nhtsa. dot. gov,” IHRA/ITS/MATTES. pdf, Tech. Rep., 2003.

[37] ISO, “ISO 26022:2010,” 2017. [Online]. Available: https://www.iso.org/cms/render/live/en/sites/isoorg-/contents/data/standard/04/33/43361.html

[38] B. Pfleging, S. Schneegass, and A. Schmidt, “Multimodal interaction in the car: combining speech and gestures on the steering wheel,” in *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’12. New York, NY, USA: Association for Computing Machinery, Oct. 2012, pp. 155–162. [Online]. Available: https://doi.org/10.1145/2390256.2390282

[39] J. L. Harbluk, J. C. Burns, M. Lochner, and P. L. Trbovich, “Using the Lane-Change Test (LCT) to Assess Distraction: Tests of Visual-Manual and Speech-Based Operation of Navigation System Interfaces,” *Driving Assessment Conference*, vol. 4, pp. 16–22, Jul. 2007. [Online]. Available: https://ir.uiowa.edu/drivingassessment/2007/papers/4

[40] M.-P. Bruyas, C. Brusque, H. Tattegrain, A. Auriault, I. Aillerie, and M. Duraz, “Consistency and sensitivity of lane change test according to driving simulator characteristics,” *IET Intelligent Transport Systems*, vol. 2, no. 4, pp. 306–314, Dec. 2008, conference Name: IET Intelligent Transport Systems.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TOH.2021.3095763, IEEE Transactions on Haptics

[41] R. Ramnath, N. Kinnear, S. Chowdhury, and T. Hyatt, *Interacting with Android Auto and Apple CarPlay when driving: The effect on driver performance: A simulator study*, Mar. 2020, number: PPR948. [Online]. Available: https://trid.trb.org/view/1694794

[42] P. Green, "Crashes induced by driver information systems and what can be done to reduce them," SAE Technical Paper, Tech. Rep., 2000.

[43] J. hwan Lee, S. P. Rd, C. Spence, and S. P. Rd, "Assessing the benefits of multimodal feedback on dualtask performance under demanding conditions," in *Proc. 22nd British HCI Group Annual Conf. on HCI 2008 , Vol.1*, 2008.

[44] T. A. Dingus, S. G. Klauer, V. L. Neale, A. Petersen, S. E. Lee, J. Sudweeks, M. A. Perez, J. Hankey, D. Ramsey, S. Gupta *et al.*, "The 100-car naturalistic driving study, phase ii-results of the 100-car field experiment," United States. Department of Transportation. National Highway Traffic Safety . . . , Tech. Rep., 2006.

[45] A. Rydström, C. Grane, and P. Bengtsson, "Driver behaviour during haptic and visual secondary tasks," in *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '09. New York, NY, USA: Association for Computing Machinery, 2009, p. 121–127. [Online]. Available: https://doi.org/10.1145/1620509.1620533

[46] J. M. Porter, S. Summerskill, G. Burnett, and K. Prynne, "BIONIC – 'eyes-free' design of secondary driving controls," *Proc. of the Accessible Design in the Digital World Conference. Dundee, UK*.

[47] S. Brewster, F. Chohan, and L. Brown, "Tactile feedback for mobile interactions," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2007, pp. 159–162.

[48] E. Hoggan, S. A. Brewster, and J. Johnston, "Investigating the effectiveness of tactile feedback for mobile touchscreens," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2008, pp. 1573–1582.

[49] A. Ng and S. A. Brewster, "Investigating pressure input and haptic feedback for in-car touchscreens and touch surfaces," in *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. Automotive'UI 16. New York, NY, USA: Association for Computing Machinery, 2016, p. 121–128. [Online]. Available: https://doi.org/10.1145/3003715.3005420

[50] K. M. Bach, M. G. Jæger, M. B. Skov, and N. G. Thomassen, "You can touch, but you can't look: Interacting with in-vehicle systems," in *In Proceedings of the 26th annual SIGCHI Conference on Human Factors in Computing Systems (CHI'08), ACM*. Press, 2008, p. 1139.

Filipe Quintal Filipe Quintal is an assistant professor at the Faculty of Exact Sciences and Engineering at University of Madeira. He is also a researcher and post-doc at the Interactive Technologies Institute, an associated Laboratory of the Laboratory of Robotics and Engineering Systems He has a background in Engineering and Computer Science, most of his research is focused in how IT can assist in everyday issues such as energy efficiency and safety.

Marco Lima Marco Lima is a master student at Faculty of Exact Sciences and Engineering in University of Madeira. His research is focused in evaluating how in-car devices can affect driver performance and vehicle safety.