HapWheel: Bringing In-Car Controls to Driver's Fingertips by Embedding Ubiquitous Haptic Displays into a Steering Wheel

Waseem Hassan, Ahsan Raza, Muhammad Abdullah, Mohammad Shadman Hashem,
and Seokhee Jeon, *Member, IEEE*

***Abstract*— Recently, there has been an excessive congestion occurring in the driving environment because of the presence of modern gadgets inside the car and increased traffic on the roads, which has resulted in a higher demand for the visual and cognitive senses. This prompted the need to reduce the demand to make driving experience safer and more comfortable. Consequently, a novel steering wheel design for in-car controls is presented in this paper. The new design introduces dual ubiquitous touch panels embedded in the steering wheel for interaction with in-car controls and haptic feedback as positive reinforcement upon successful execution of an in-car control. There are eight different functionalities that can be controlled using the embedded touch panels. The proposed system is compared with a standard car regarding its efficacy using the NASA task load index (NASA-TLX) evaluation technique. The results showed that the proposed system significantly reduced the drivers' visual, cognitive, and manual workload.**

***Index Terms*— Haptic interfaces design, steering design, vibrotactile actuator, in-car controls.**

I. INTRODUCTION

DUE to the increase in traffic condition complexity and presence of numerous gadgets inside a car, modern-day driving needs a higher degree of visual and cognitive attention from drivers, in which approximately 95% of the information is, acquired visually [1]. While driving, a person is visually occupied but has to do certain minor yet attention-diverting tasks such as adjusting the thermostat, turning up the radio, or manipulating other controls inside a car. Such tasks can lead to sensory burden that can cause fatigue, which may lead to cognitive failure [2]. Because of this, there arises a need to share some of these functions with other modalities. A study showed that drivers took less time and committed fewer errors in a navigation task when provided with both haptic and auditory cues compared to auditory only [3]. Another study reported that drivers reacted faster to a navigation message on a tactile display compared to a visual-only display and perceived lower workload and mental effort using the tactile display [4]. Auditory and visual channels have been used; however, these channels can be public and noisy or may have communication delays. Visual sense is already involved in the driving task, so adding visual cues for secondary tasks runs the risk of reducing the margin of safety. Auditory cues can be masked by ambient background noise/music [5] or by conversations of passengers [6]. Auditory cues may also suffer from "inattentional deafness" where people miss auditory information due to the presence of high visual load [7], [8]. On the other hand, tactile information is transferred privately, silently, and instantly. The tactile channel is considered to be underutilized and less central in a driving environment unlike visual and auditory channels [9]–[11]. Therefore, the the tactile channel is found to be a good resource to use for in-car controls while the driver is visually occupied [12]–[15].

The location of these controls is just as important as their mode of interaction with the in-car controls in order to minimize driver distraction. In the automotive context, distraction can be classified as manual, visual, and cognitive distractions [16]. It is called a manual distraction when the driver's hands have to move to interact with other controls. The more the hands have to move, the higher the risk of manual distraction. Visual distraction occurs when a display requires the driver to look away from the road while driving. The distance and the direction of the eye movement are factors in such a distraction [16]. Cognitive distraction involves the mental effort that goes into processing these interactions. Although naturally the in-car controls appear to be not important, they can still divert the attention of the driver for a moment from their primary task that is driving. These tasks can lead to cognitive failures, in which the driver notices some objects/traffic but fails to register them in their mind [2]. A steering wheel and in-car controls should have an ideal design that minimizes all types of distractions, allowing the driver to concentrate on the road.

In this paper, we propose a novel, simple, and innovative system for interacting with the in-car controls. We introduce a steering wheel embedded with two displays (touch panels) running along its (outer and inner) perimeter, as shown in

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The authors are with the Department of Computer Science and Engineering, Kyung Hee University, Yongin-si, Gyeonggi-do 17104, South Korea (e-mail: waseem.h@khu.ac.kr; ahsanraza@khu.ac.kr; abdullah@khu.ac.kr; ayon7019@khu.ac.kr; jeon@khu.ac.kr).

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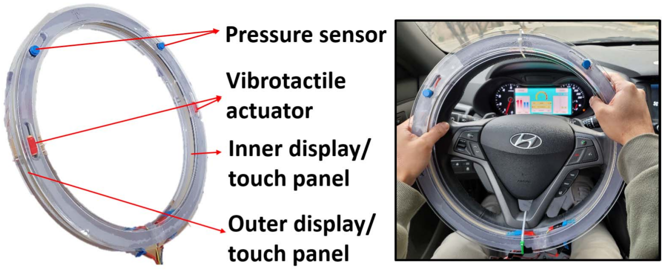

Fig. 1. (left) The prototype steering wheel. (right) The prototype mounted on a standard wheel for the evaluation experiment.

Fig. 1. One display is located on the inner side of the wheel while the other on the outer side. These displays function as interfaces for operating or interacting with the different in-car controls. The driver can access the controls with short finger movements since the displays run along the entire perimeter. To interact with the displays, the driver can perform short up and down swipes along the direction of the rim. This mode of interaction is easy to remember and effortless to execute, and it does not require visual confirmation. User interaction is detected by the displays, interpreted by the central control module, and executed in the form of engaging in-car controls. Upon doing an action, the user also receives an associated positive reinforcement feedback. This feedback is empirically designed to represent the given action, e.g., the feedback for an indicator (turn signal) is a low-frequency pulsating signal to mimic the sound of the blinker. As a proof of concept, eight different functionalities (in-car controls) are controlled based on a user's interaction with the displays. However, more functionalities can easily be added into the system without significant overhead.

The advantages of using such a display are as follows:

- It reduces the workload needed to engage in in-car controls, and allows the driver to maintain better focus on driving.
- Since the controls are located on the wheel's perimeter, drivers can adjust in-car controls with minimum hand/finger movement while maintaining their favored gripping position.
- The display is embedded inside the steering wheel and is unobtrusive during a normal operation of the steering wheel; thus, it will not change the traditional feel or ergonomics of a steering wheel.
- The system can be easily deployed into most types of existing cars because it does not require significant modifications and it is easily integrable.

In the remaining sections of this paper, we highlight some of the previous studies conducted in the field of haptic feedback on the steering wheel and the steering design itself. The current system is compared to other existing works in Sect. II. In Sect. III, the working principle of the system is explained as well as all the details about its hardware and software components. Section IV discusses a psychophysical experiment that evaluates the haptic and design aspects of the system. Lastly, the system's capabilities are presented in light of the experimental results in Sect. V.

II. RELATED WORKS

The current study introduces a novel interaction methodology for the in-car controls as well as the use of haptic feedback in the steering wheel to help reduce driver workload. Therefore, it is necessary for us to discuss the stance of the proposed system considering the recent advances in steering wheel design and haptic feedback on a steering wheel along with the previous efforts for workload management in a driving environment.

A. Haptic Feedback

Haptic feedback is considered to be an effective way in delivering information while a person remains in constant contact with the steering wheel. The studies related to haptic feedback can be broadly categorized into two functionalities: warnings or alert systems and guidance or assistance systems [17].

The warnings or alert systems inform the driver about an unintended situation but do not provide any assistance to counter the given situation, e.g., lane departure alerts [18], navigation systems [19], [20], proximity alerts [13], etc. On the other hand, guidance systems assist the driver by providing force feedback to various degrees depending on the application while driving a car, e.g., lane assistance [21], curve handling, collision aversion [22], etc.

These approaches show the advantages of using the haptic channel in providing assistance/alerts. However, haptic feedback is usually provided based on external events, such as lane crossing on a highway or another vehicle approaching their blind spot. A driver may be alarmed by suddenly receiving such kind of a haptic feedback, and they may need a moment or two to understand the situation; therefore, the haptic feedback can be disruptive or misleading in certain scenarios [23], and the user has to memorize the various alert forms/combinations. In the proposed system, an action is initiated by the user, and haptic feedback is provided upon execution through positive reinforcement. Additionally, the user does not have to remember any alert combinations because these alerts are considered to be reinforcement rather than a precursor to an event.

B. Workload Assessment

The complexity of a driving situation is based on multiple factors, i.e., interacting with in-car controls, controlling the car, comprehending the incoming visual information from surroundings, etc. As the driver needs to receive and comprehend all incoming information while driving, sufficient mental and physical resources are required to successfully complete the driving task. Such a task uses multiple senses, and it can result in a high amount of workload for the drivers, which may lead to cognitive failure. Specific tasks that may lead to higher workload can be identified by workload rating procedures. Therefore, workload assessment plays an important role in guiding a designer to fine-tune a system in such a way that the overall workload is either mitigated or reduced.

In a driving environment, as mentioned earlier, a higher workload may lead to sensory burden, which can cause different distractions, such as cognitive, manual, and visual distractions [16]. There are various methods in identifying the quantitative and qualitative driving workload. The quantitative workload assessment techniques deal with eye movement data [24], [25], body movement data [26], etc. One of the most famous techniques for qualitative and quantitative workload assessment is the NASA task load index (NASA-TLX) [27], which has been used in automotive context to determine the driving workload [28], [29]. In the proposed system, we performed workload measurement using NASA-TLX to estimate the driver's workload while interacting with in-car controls in a moving car.

C. Steering Wheel Interaction Design

A driver's primary job is to drive safely, which can be achieved by allocating sufficient visual and mental resources to the driving task. All other control elements inside a car have to be installed accordingly for the primary task to be facilitated. Most of the controls in earlier vehicles are located in the dashboard area. However, today, some controls are placed along the perimeter of the steering wheel for easy access and to reduce driver distraction.

At present, some modern systems make use of the complete front side of the steering wheel (including the rim) as interface. Some examples include the use of touch gesture interface [30], touch screens [31], and multimodal displays [32]. In addition, the backside of a steering wheel has also been used as a touch panel. Several haptic displays including braille keys [33], sliders [34], and force sensors [35] have been embedded to the back of the steering wheel for various applications.

Performing a control needs the movement of one or both hands away from the steering wheel. Similarly, the use of touch screens or buttons (front of the steering wheel) mostly requires the driver's visual attention, while a driver's cognitive energy is needed when using the touch panels (back of the steering wheel). Such executions require the drivers to learn different kinds of gestures needed for the controls. However, collectively, these displays can distract drivers and may result in reduced road safety. In our proposed system, the location of the haptic panels is found around the rim, which does not require the driver to remove their hands from the steering wheel. Also, the touch-based displays do not need visual attention. Lastly, the mechanism in operating the controls is just a single up or down swipe; thus, significant cognitive effort is not a requisite for such an operation.

III. SYSTEM DESIGN

The proposed system is a new design for interacting with in-car controls and providing haptic feedback as positive reinforcement upon execution. In Fig. 2, a brief explanation of the overall system is presented. First, the system continuously monitors any contact from the user. When the user interacts with the haptic panels, the central control module receives and interprets the command signal. Depending on the action of the user, the control module reflects the appropriate changes through a GUI and sends a corresponding haptic feedback. The different parts of the system and all the in-car controls present in the prototype will be explained in detail in this section.

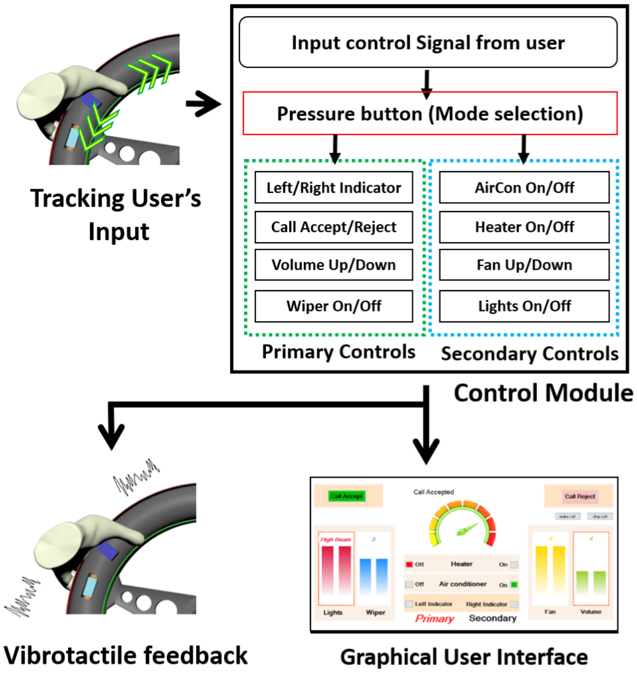

Fig. 2. An overview representing the various modules and the overall flow of the system.

A. Hardware

As shown in 1, the central part of the system is the prototype of a steering wheel made from a polycarbonate material. The concept of the new design was to provide haptic interaction points where the user can interact with the controls using hand or finger swipes. After careful consideration, it was concluded that an intuitive location for the swipes happened to be along the outside and inside rims of the steering wheel. Therefore, the steering wheel was designed with grooves on the inside and outside of the rim.

After coming up with the location of interaction, the mode of interaction had to be discussed. An ideal sensor would be one that could detect both the location and the length of interaction. For such a purpose, a touch screen or an electrostatic friction display was initially considered. However, finding an off-the-shelf curved touch screen or friction display was challenging. At the same time, producing a specific display was also not feasible due to its high cost. Therefore, it was decided to use thin-film flexible potentiometers (SoftPot membrane potentiometer, length = 500 mm, resistance range = 100 ohms to 10000 ohms) as an interaction point. The potentiometers were flexible and readily available in various sizes, solving our problem in curvature. The resistance of a potentiometer changes depending on where it is touched by the user. This property helped in determining the length and direction of a swipe every time there is an interaction. They were installed in the grooves (on the outside and inside of the steering wheel) to detect any haptic contact from the user when interacting with the in-car controls. The location of the potentiometers is found inside the grooves to avoid accidental contact during normal operation. A single potentiometer covers half of the rim's circumference; thus, there are four potentiometers mounted on the steering wheel (two in the inside groove and two in the outside groove).

The next step was to provide haptic feedback to the users. First, the strength of the haptic feedback had to be high enough for the moving car's inherent vibrations to not override it. Second, the form factor of the actuator had to be adequately compact to fit inside a steering wheel. Various vibrotactile actuators were tested, and the haptuator (MM3C-HF from Tactile Labs, resonance frequency = 85 Hz) provided a good size-to-vibration ratio (based on empirical judgment). Two haptuators were used to provide tactile feedback.

These were placed in designated slots (of exact size, i.e., 36 × 9.5 × 9.5 mm) on the front of the rim located on opposite sides. The slots have exact sizes to ensure a perfect fit and avoid any unwanted vibrations due to loose placement of the actuators.

A single potentiometer can represent one operation at a time. There are four potentiometers and eight functionalities. A single potentiometer was needed to be reused for multiple functionalities. For this purpose, two pressure buttons (push-button switches) were also embedded into the opposite sides of the rim. These were used to switch between functionalities

The interaction data from the potentiometers and switching data from pressure buttons were collected using a data acquisition unit (NI DAQ USB-6351, data sampling rate = 150 sample/second) and sent to a control module (laptop). The control module updates a GUI and sends a corresponding command signal to the vibrotactile actuators that provide feedback.

B. In-Car Control Functionalities

Currently, there are eight different in-car functionalities that can be executed using our system. The eight functionalities are divided into two groups: primary and secondary controls. Primary controls are those used more frequently, while those used less often are labeled secondary. The full details of all eight controls are provided in Table I.

A user can switch between the primary and secondary controls by simultaneously pressing both the pressure buttons. To avoid unintentional execution, two pressure buttons are used; such accidental operation may happen if there is only a single button. A user interacts with the touch panel through swiping up or down along the rim's circumference. In a normal gripping position, a user interacts with the inner haptic display using the thumbs and with the outer display using one or more of the other four fingers. Among the controls, four of them require a single swipe for activation. These are the indicators, calls, air conditioner, and heater functions. The other four controls, i.e., lights, wiper, volume, and fan, need a longer swipe regarding distance covered by the finger (or multiple short-distance swipes). A single swipe increases the value by one unit; however, a longer swipe can cause a higher increase in number depending on the swipe length. The location of all the controls is depicted in 3.

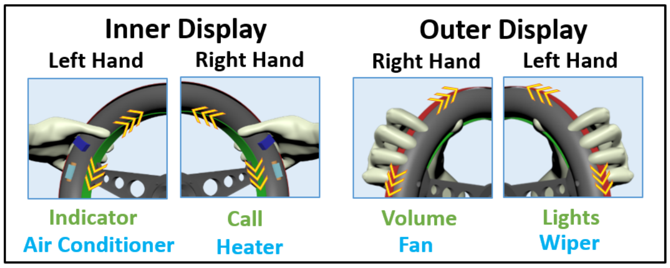

Fig. 3. Details about the location and operation of the primary and secondary in-car controls.

TABLE I

DETAILS OF ALL THE PRIMARY AND SECONDARY IN-CAR FUNCTIONALITIES ALONG WITH THEIR DETAILS

Mode	Controls	Levels
Primary	Lights	Low/Medium/High
	Volume	Up/Down (1-8)
	Indicators	Left/Right
	Call	Accept/Reject
Secondary	Wiper	Up/Down (1-4)
	Fan	Up/Down (1-4)
	Air Conditioner	On/Off
	Heater	On/Off

C. GUI and Control Module

A simple GUI was designed to provide visual reflection of the manipulation of in-car controls. A screenshot of the GUI is given in Fig. 2 and in the supplementary material. It presents the current state of all the in-car controls. All functionalities are directly manipulated from the touch panel inputs; however, there is a special button for creating a call event as we cannot receive or reject a call unless there is an incoming call. The *make call* button is used to create an incoming call event. The GUI was created as part of the prototype to visualize the system's output. In a real car scenario, the associated functionalities in the system would be activated by the outputs, and thus a GUI would be unnecessary.

The control module interprets the user's input. The input can either be from a user swipe or from the pressure buttons. If the user simultaneously presses both pressure buttons for two seconds, the control module changes the functionality of the touch panels from primary to secondary mode or vice versa. If the input is from one of the touch panels, the control module identifies the swipe direction and changes the current state of the corresponding in-car control. Lastly, an appropriate haptic feedback signal is sent to the actuators, and the GUI is updated.

D. Haptic Feedback Design

As mentioned earlier, the driver receives a haptic feedback after successfully executing the in-car controls. One key aspect of the proposed system is that the feedback sent to the driver should be in connection with the executed operation, allowing the feedback to work as positive reinforcement for the action of the driver. With this, the haptic feedback for the in-car controls was empirically designed to present the association of the corresponding actions.

TABLE II

DETAILS OF ALL THE PRIMARY AND SECONDARY IN-CAR FUNCTIONALITIES ALONG WITH THEIR DETAILS. THE PEAK TO PEAK VOLTAGE (AMPLITUDE) WAS FROM −2.5 TO 2.5 volts. F = FREQUENCY, D = DURATION, INDEFINITE = UNTIL AN ACTION IS PERFORMED

In-Car Control	**Feedback**	**F (Hz) / D (ms)**
Lights Up/Down	Step-wise increasing sine	50 / 200
Volume Up	Step-wise increasing sine	50 / 200
Volume Down	Step-wise decreasing sine	50 / 200
Wiper Up	Step-wise increasing sine	50 / 200
Wiper Down	Step-wise decreasing sine	50 / 200
Fan Up	Step-wise increasing sine	50 / 200
Fan Down	Step-wise decreasing sine	50 / 200
Indicators	Added sinusoids	3 + 5 / 3000
Call Accept	Short increasing exponential	150 / 1000
Call Reject	Short decreasing exponential	150 / 1000
Incoming Call	Added sines	55 + 61 / indefinite
Air Conditioner	Short burst sine	40 / 500
Heater	Short burst sine	40 / 500
Mode 1	Single beep sine	25 / 300
Mode 2	Two beep sine	25 /300

A vibration signal contains different parameters such as amplitude, frequency, and duration, which contribute toward the appropriate design of haptic feedback [36], [37]. A toolbox known as hapticons has been developed to allow users to create specific vibration signals by manipulating different factors, i.e., waveform, amplitude, and frequency [38]. In their study, Park *et al.* used a combination of such parameters to produce a vibration signal to augment haptic feedback on a physical button [39]. Abdullah *et al.*, on the other hand, tuned the signal parameters for different types of waves to create haptic logos [40]. In our study, we focused on using similar parameters found in the literature to design a particular feedback for each in-car control. The full details of the feedback for each in-car control are presented in Table II. It can be seen that some controls have a short and subtle haptic feedback, while others have longer feedback. For instance, normal indicators give off a blinking sound; therefore, keeping true to that effect, the feedback for the indicators is the addition of two sinusoids (3 Hz + 5 Hz). The volume feedback, on the other hand, is reflected by an increase or decrease in the amplitude of the feedback signal. This changing feedback helps the driver to assess the volume level without looking at the visual display. There are other controls that only exhibit an on/off or a click-type nature, i.e., air conditioner, heater, etc. The controls have feedback of a short and sharp sinusoidal burst. It should be noted that the feedback was empirically designed with efforts for it to be closely associated to the given controls.

E. Design Refinement Process

In the field of human-computer interaction (HCI), finalizing the design of a prototype or a system goes through an iterative process. The developers introduce an initial idea for the prototype, which is then tested by users for improvements and feedback. A final design is reached upon after several of these iterations. The same process was followed in achieving the current state of the proposed system.

Initially, the touch panels were attached on the outer and inner rims of the steering wheel prototype. In the pilot experiment, this caused a number of unintended interactions. To counter this, 5-mm deep grooves were made along the outer and inner rims for the touch panels. The grooves completely stopped the unintended interactions as the hands could rest on the ridges of the grooves during normal gripping position.

Originally, the functionalities were randomly assigned to the different parts of the steering wheel. A group of users noted that it was difficult to keep track of all the functionalities. Another group commented that it was unnatural to use thumbs for longer swipes, e.g., increasing the volume. To clarify this, the thumbs are used to interact with the inner touch panels. Based on these responses, the functionalities were categorized into two groups: the binary operations and the multilevel operations. The binary operations were indicators, call accept/reject, air conditioner on/off, and heater on/off. The other group was composed of lights, volume, wiper, and fan. All the binary operations were placed on the inner touch panels, while the others were placed on the outer touch panels. Thus, the thumbs had to make short swipes, while the other fingers were used to make longer swipes (if necessary).

IV. EVALUATION EXPERIMENT

The current system proposed changes to the steering wheel design as well as provide a haptic feedback as positive reinforcement, in an effort to minimize driver distraction and workload. NASA-task load index (NASA-TLX) is a widely used evaluation technique for multidimensional workload rating. This procedure identifies the participants' workload while performing a certain task [27]. As mentioned earlier, the current system strives to reduce three kinds of distractions while driving, i.e., manual, visual, and cognitive. The NASA-TLX questionnaire already contains factors that determine the manual (physical demand, temporal demand, and effort) and cognitive workload (mental demand and frustration); however, it does not have any factors to identify visual workload. Because of this, a visual workload factor was added to the questionnaire. In this experiment, the participants were asked to compare their experience in a real car with the current system. The current system was presented in two different conditions, i.e., with and without haptic feedback.

In addition to the NASA-TLX score, a Weighted Workload (WWL) score was also calculated by underlining the significant factors in the questionnaire. The NASA-TLX score weighs all the factors equally; however, all the factors might not contribute fairly to a specific workload. Therefore, the participants are asked to compare the factors and assign weights to them. To achieve a WWL score, the weights of individual factors are multiplied with the ratings on these factors. The WWL can be considered a more precise representation of the workload because it enhances the effect of the factors contributing more to the workload variation.

A. Participants and Procedure

There were 34 participants (27 males and 7 females) in this experiment. Their average age was 29.6 years (ranging from 21 to 36 years). All participants were experienced drivers with a minimum of three years of active driving experience.

It was necessary to recruit only experienced drivers to keep the experiment fair as inexperienced drivers might bias the data due to their limited driving ability

To confirm that the sample size of 34 participants can provide statistically significant results, a statistical power analysis was conducted. The power analysis combines research area knowledge, statistical analysis, and application-specific requirements to calculate a minimum sample size for the experiment. To calculate the minimum required sample size, the power analysis needs the expected difference between the two conditions, an assumed standard deviation, the desired p-value, and the desired power value. The sample size calculations were conducted using a two-sided (or two-tailed) test with equal group sizes [41]. The formula used for sample size estimation [42] is

$$N = \frac{4\sigma^2(z_{crit} + z_{pwr})^2}{D^2} \tag{1}$$

where N is the estimated sample size and σ is the assumed standard deviation, z_{crit} is the Z value for the given p-value, z_{pwr} is the Z value for the statistical power value, and D is the minimum expected difference between the two means. In the present experiment, the expected difference between the means of the two conditions was set at 20 after the preliminary studies. A difference of 20 out of 100 demonstrated a reasonable perceptual difference for the two conditions. The significance level was set at $p = 0.05$ (alpha) ($z_{crit} = 1.96$), the power was set at beta $= 0.95$ ($z_{pwr} = 1.64$), and the standard deviation at 15 rating points (out of one hundred). The power value represents the probability of an effect being captured if it exists in the data; therefore, a higher value of power is desirable. According to 1, the calculations presented a minimum sample size of 29.23 participants for the current study. Erring on the side of caution, a sample size of 34 was considered to guard against possible outliers in the experiment.

The experiment was conducted as a psychophysical study where the participants were asked to rate their experience with a standard car steering wheel (Hyundai Veloster 2016) and our proposed steering wheel. The proposed steering wheel was mounted on top of a standard steering wheel, as shown in Fig. 1. Using the proposed steering wheel, the participant could monitor the present state of the in-car controls through a small screen placed on the odometer. The rating was carried out on the standardized NASA-TLX questionnaire with an additional visual workload question (questionnaire available in the supplementary material).

The participants studied and familiarized the steering wheels for 10 to 15 minutes. Afterward, they interacted with the steering wheels (standard and proposed) while following a list of tasks narrated by the experimenter (one task at a time). There were a total of ten tasks for each steering wheel condition, as given in Table III. The participants had to perform all the tasks for each condition in the experiment while driving along a straight road. The task list contained functionalities that a driver would perform in a routine drive. The order of tasks was randomized, and the order of conditions was block randomized. The overall experimental setup is shown in the supplementary material.

TABLE III

A LIST OF THE TEN TASKS THAT THE PARTICIPANTS WERE ASKED TO PERFORM ON EACH OF THE STEERING WHEEL

S.No	Details of Task
1	Increase volume level to maximum and then decrease it to half
2	Accept a call once and then disconnect. Second time reject a call
3	Increase lights to high beam and decrease to low beam
4	Turn on indicators in the following order: left, right, left
5	Turn on air conditioner
6	Increase fan up to third level
7	Turn on heater
8	Turn off heater
9	Decrease fan to zero
10	Increase wiper speed to level 2
*	Switch mode to primary/secondary (where applicable)

The participants rated their task workload on seven factors after each condition. Subsequently, pairwise comparisons were made between the seven factors according to the level of workload diversity they provided. In total, there were 21 pairwise comparisons for the seven factors. The total number of times a given factor was chosen made up the weight of that particular factor. This exercise was carried out to put a higher numerical emphasis on the rating factors that the participants thought to be more important in the given scenario. On average, one experiment lasted 60 minutes.

B. Data Analysis and Results

The result of the evaluation experiment presented two kinds of data: rating data for the three experimental conditions and weights of the individual factors. The rating data were from 0 to 100 and were averaged across all participants. The highest weight value for a given factor was six. The WWL is achieved by multiplying the individual factor ratings with their associated weights for each participant. The product was divided by 21 (the sum of all weights) to get a WWL value between 0 and 100. A lower WWL score depicted a task that has a lesser workload. The WWL score was calculated separately and then averaged across all the participants.

In Fig. 4, the raw NASA-TLX rating scores are presented. It is apparent that the proposed system with haptic feedback performed the best across all the individual factors. A one-way analysis of variance (ANOVA) was conducted to observe the mean and statistical difference between the conditions. The post hoc comparison was carried out using the Tukey-Kramer method. The results showed that the mean values for the proposed system with haptic feedback were statistically significantly ($p < 0.05$) better than the standard car steering wheel across all the individual factors, except *performance*. It should be noted that the *performance* scale was inverted from its original NASA-TLX format to match with the other scales. A smaller *performance* value shown in Fig. 4 represents a better subjective rating value. Meanwhile, the proposed system without haptic feedback was rated as statistically similar to the standard car steering wheel across all the factors, except *physical demand* and *temporal demand*. The high values of standard deviation show that certain aspects of the system attracted much attention from the participants than others; however, the overall trend presents that the proposed system with haptic feedback was preferred over the other two.

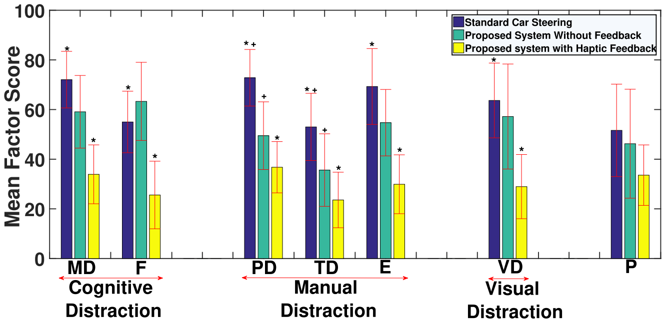

Fig. 4. The averaged ratings from modified NASA-TLX questionnaire (Visual demand factor included in NASA-TLX). The error bars show the standard deviation for each bar. (* and + mean $p < 0.05$). (MD = mental demand, F = frustration, PD = physical demand, TD = temporal demand, E = effort, VD = visual demand, P = performance.)

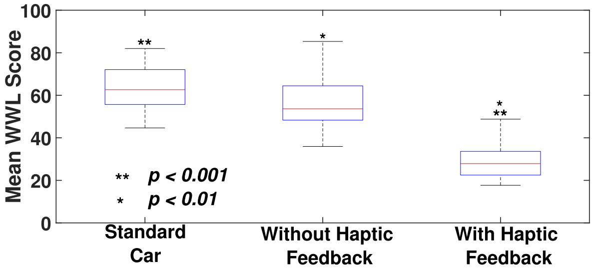

Fig. 5. The mean WWL scores are represented in the form of a box plot for all the three experimental conditions.

A box plot with the average WWL scores is given in Fig. 5. The one-way ANOVA showed that the mean WWL value of the proposed system with haptic feedback was statistically significantly better than the other two with a p value less than 0.01. The WWL score for the proposed system without haptic feedback and the standard car showed a higher degree of variation around the mean value across different participants, whereas the proposed system with haptic feedback presented with relatively less variance.

V. DISCUSSION

The proposed system's main goal was to provide an innovative and simple design for interacting with in-car controls. Because of this, a new steering wheel prototype was designed with haptic feedback as positive reinforcement. Two contributions form the core of the proposed system: the new steering wheel design was hypothesized to provide drivers a better and easier in-car interaction experience, while the haptic feedback was theorized to provide confidence and acknowledgment of a successful operation. Therefore, the evaluation experiment was designed to test these theories.

After getting familiar with the steering wheel during the practice session for 10–15 minutes, the participants were confident in using the proposed system. The proposed system with haptic feedback outperformed the standard steering wheel across all the factors. The specific design of the haptic panels, their location, and the mode of interaction could be the factors of such a performance. The haptic panels are placed around the steering wheel, thus not requiring the driver to change their hand positions on the steering wheel. As the panels are hidden from direct sight and are only accessible through the fingertips, visual attention is deemed not necessary. Additionally, the ease of use of the haptic panels could be another aspect of the proposed system that could have made the participants to rate it higher. The panels have intuitive commands, which can be executed through a simple up or down gesture for all the controls. Lastly, the haptic feedback as positive reinforcement ensured the participants that they were operating the correct command.

In the evaluation experiment, three different conditions were compared, i.e., a standard steering wheel and the proposed system with and without haptic feedback. The proposed system without feedback was included to test if haptic feedback affects the experience or perception of the users. In Figs. 4 and 5, it is shown that the participants rated both the proposed system without haptic feedback and the standard steering wheel similar to each other, having no significance difference. This means that the learning curve of the proposed steering wheel design was easy, making the participants to quickly adapt to it. From Figs. 4 and 5, it can be seen that the proposed system with haptic feedback is significantly better. These results showed that providing haptic feedback as positive reinforcement significantly improved the system.

The other purpose of the evaluation experiment was to test the design and effectiveness of the proposed steering system. As discussed earlier, NASA-TLX is used to measure the task workload. A higher workload while driving would mean a higher chance of distractions for drivers. There are three basic types of distractions in driving context, i.e., manual, cognitive, and visual distractions. The raw NASA-TLX already contains inherent factors, which can be used for manual and cognitive workloads/distractions, but it does not contain any visual workload factors. The NASA-TLX factors that can be related to manual distraction are physical demand, temporal demand, and effort, while those related to cognitive distractions are mental demand and frustration. It is evident from Fig. 4 that the proposed system with haptic feedback reduced workload according to several dimensions.

In the experiment, participants were asked to assign weights to the individual factors using pairwise comparisons. Upon closer inspection of these weights, it was found that *performance* was considered as one of the highly significant factors for the given tasks, as shown in Fig. 6. This suggests that participants found *performance* to be highly relevant in providing workload variation in light of the task at hand and assigned high weights to it. However, according to the one-way ANOVA, there was no significant statistical difference in the *performance* weights across the three experimental conditions (p=0.39). This was most likely because the task itself was not too difficult and most of the participants felt that they successfully completed the task across all three experimental conditions.

VI. LIMITATIONS AND FUTURE WORK

The eight functionalities used in the current system are some of the highly used controls; however, there are other controls that are currently not available in this system,

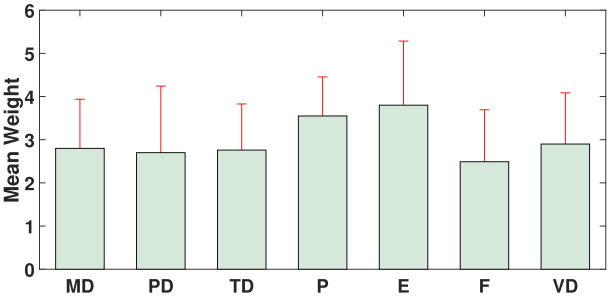

Fig. 6. The mean weights assigned to the modified NASA-TLX factors. Error bars are showing the standard deviation.

e.g., side mirrors, windows, door locks, etc. One solution to include more controls would be to make the steering wheel more dynamic, where the user can manually add functionalities and their locations on the wheel.

As discussed, a user receives a haptic feedback after successfully executing an in-car control. This haptic feedback was empirically designed and an effort was made to associate the haptic feedback with the intrinsic nature of the controls. However, there lies a need to conduct a detailed study where users are asked to associate haptic feedback to the in-car functionalities, similar to the study conducted in [40].

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Waseem Hassan received the B.S. degree in electrical engineering from the National University of Science and Technology (NUST), Pakistan, and the M.S. degree in computer science and engineering from Kyung Hee University, Republic of Korea, where he is currently pursuing the Ph.D. degree with the Department of Computer Science and Engineering. His research interests include psychophysics, and haptic texture perception and augmentation.

Ahsan Raza received the B.S. degree in computer engineering from the University of Engineering and Technology (UET), Taxila, Pakistan, in 2015. He is currently pursuing the Ph.D. degree with the Department of Computer Science and Engineering, Kyung Hee University, South Korea. His research interests include mid-air haptic feedback, haptic texture augmentation and perception, and psychophysics.

Muhammad Abdullah received the B.S. degree in electrical engineering from the National University of Science and Technology (NUST), Pakistan. He is currently pursuing the M.S. degree with the Department of Computer Science and Engineering, Kyung Hee University, Republic of Korea. His current research interests include encountered-type haptics devices and virtual reality.

Mohammad Shadman Hashem received the B.S. degree in mechanical engineering from the Chittagong University of Engineering and Technology, Bangladesh, in 2018. He is currently pursuing the master's degree in computer science and engineering with Kyung Hee University, South Korea. His research interests include haptics, virtual reality, and human–computer interaction.

Seokhee Jeon (Member, IEEE) received the B.S. and Ph.D. degrees in computer science and engineering from the Pohang University of Science and Technology (POSTECH) in 2003 and 2010, respectively. He was a Post-Doctoral Research Associate with the Computer Vision Laboratory, ETH Zurich. In 2012, he joined the Department of Computer Engineering, Kyung Hee University, as an Assistant Professor. His research interests include haptic rendering in an augmented reality environment, applications of haptics technology to medical training, and usability of augmented reality applications.