FabriCar: Enriching the User Experience of In-Car Media Interactions with Ubiquitous Vehicle Interiors using E-textile Sensors

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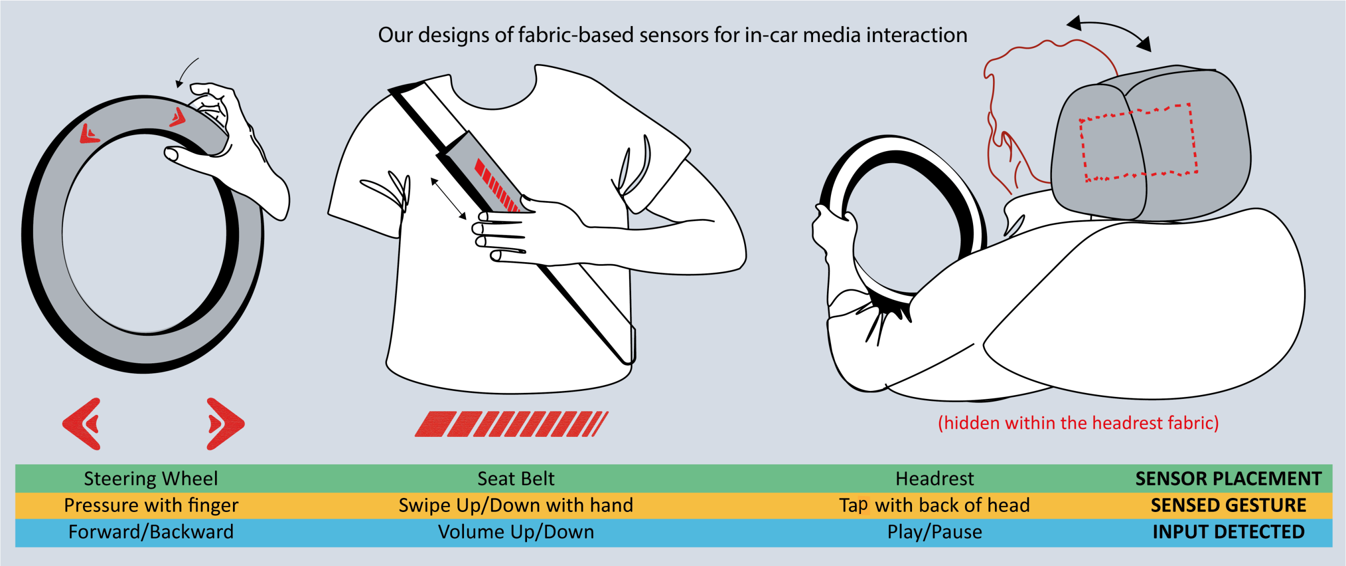

Steering Wheel	Seat Belt	Headrest	**SENSOR PLACEMENT**
Pressure with finger	Swipe Up/Down with hand	Tap with back of head	**SENSED GESTURE**
Forward/Backward	Volume Up/Down	Play/Pause	**INPUT DETECTED**

Figure 1: Our designed fabric-based sensors for tactile vehicle interaction using e-textiles on car leather surfaces.

ABSTRACT

This work explores e-textiles in the design space of Human-Vehicle Interaction (HVI) and compares distraction levels between e-textile and screen-based interactions during driving tasks. We developed three prototypes (in the steering wheel, headrest cover, and seat-belt pad) to support tactile interactions (tap, press, and swipe) with car interior elements for non-driving applications (such as media control). Our designs used digital embroidery to achieve aesthetic design qualities and wireless connection. In a deployment study with 16 participants, we collected quantitative and qualitative data through video recording, field observations, and user interviews. The study repeated all scenarios using screen-based interaction for comparison. Our findings present insights into fabric-based sensors including fewer collisions and a 302.7% decrease in eye distraction. These findings suggest new design opportunities, such

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as retrofitting existing vehicles, designing ideation toolkits for diverse users, devising an e-textile Fitts' Law for reachability, and expanding vehicle interaction research within the HCI community.

CCS CONCEPTS

• **Human-centered computing → Human-Computer Interaction**.

KEYWORDS

e-textiles, smart textiles, vehicle, interior, car, automotive, sensors, non-wearable

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1 INTRODUCTION

Consumer vehicles are increasingly incorporating touchscreens into in-vehicle environments, but previous research has highlighted how this design trend might increase the risk of distracted driving [2] and driving fatigue [54]. To address this, there is an increasing need for HCI researchers to understand how humans can interact with the interfaces of in-car systems in a more efficient and pleasant way given the amount of time individuals spend within these spaces [73]. Car interfaces are currently undergoing a dramatic transformation in two key dimensions: infotainment technology development and vehicle interior design. First, novel information and communication technologies are changing how we interact with our cars, converting them into infotainment spaces [64]. Second, modifications on the design of vehicle interiors are opening the door for unprecedented non-driving activities and transforming cars from transportation vehicles to living spaces [107].

These two influential and intertwined dimensions create opportunities for revisiting our current notion of Human-Vehicle Interaction (HVI) and focusing on how people experience an interactive moving space. Yet, while cars are still remain driving spaces, solving the engineering problems of how to build effective, efficient, safe, and reliable vehicles is of utmost importance.

This makes the current design trend towards (and user demand for) integrating smart devices into cars problematic, either as Bring Your Own Device (BYOD) or transforming the dashboard into a digital screen with multi-touch and speech-based input. For example, in previous research the Tesla Model 3 diverges from design heuristics [1, 91]. Apart from the steering wheel, knobs, and pedals—which have followed the same design pattern and remained roughly unaltered over the decades—most current in-car interactions lack physical tactility. Research on developing novel tangible, embedded and embodied interactions within car interfaces has been overshadowed by cutting-edge in-car technologies. Analyzing the current literature on HVI, we have identified a gap between the current efforts of related work and the vision of ubiquitous interaction [126] using tactile/tangible interfaces within the in-car environment.

In the limited academic work on tangible interaction within cars, the focus is predominantly on interfaces for driving-related activities, either communicating the state of the car to the driver in autonomous cars [27, 36] or assisting drivers with easier and more efficient driving in human-driven cars. For example, researchers have explored haptic feedback and vibration on the steering wheel [56], on the waist [7] and on the seat [26] for navigational cues representation. As the number of factors influencing the design space for automotive user interfaces increases, we will need new approaches for tangible user interfaces (e.g. e-textile interfaces) and spatial interaction design [58].

In this paper, we explore e-textiles in the design space of automotive user interfaces, our interfaces leverage the textile surfaces within vehicles (see Figure 1), in comparison to screen-based interfaces on the dashboard in human-driven cars (SAE level 0, 1, and 2). We center our focus on textile interfaces due to the ways vehicle interiors are currently designed with a myriad of fabric and leather surfaces. As such, we can leverage these textile surfaces to encourage seamless, less focus-demanding interactions by adopting e-textile techniques. By seamless, we mean “the idea of integrating computers seamlessly into the world at large” [22, 126], and interacting without interruption. This paper discusses novel interactions for drivers through textile surfaces such as the seat-belt, steering wheel and headrest, and how e-textiles can potentially improve drivers' in-car user experience.

Through this research, we leverage the concept of ‘interioraction’, which Nabil et al. [82] define as blending interior design and interaction design. In the ubiquitous computing era, interactions are not confined to touchscreen and buttons; they can be embedded “in everything” such as walls, chairs, and cars [127], which can act as spatial extensions of displays in different interactive environments [103].

Our vision is to design our automotive interactive spaces as places where we can live, work, and socialize together. Utilizing fabric and leather surfaces as seamless car interfaces can be one of the ways to engage users in ubiquitous non-driving-related activities (NDRAs) within future car interiors. The NDRAs are generally activities which don't have the primary purpose of “increasing driving safety or performance”, as proposed by Pfleging et al. [97], such as media control, infotainment, gaming, and social engagement. Such aesthetically-integrated form factors have been promoted in recent research as a means of enriching our interaction with everyday things in our existing environment [65, 79, 85]. However, challenges in the design of meaningful and robust e-textile interfaces remain a research gap [16, 29, 116].

The two key research questions (RQs) of this paper are: RQ1) How do people experience and reflect on interacting with e-textiles sensors versus screen-based interactions while driving?; RQ2) What is the difference between people's felt experience and the quantitative measured data?

In this paper, we present the design and deployment of textile-based sensors integrated within the faux-leather covers of the steering wheel, seat-belt, and headrest through digital embroidery. We then discuss our user study with 16 participants to compare the difference between the user experience of driving while interacting with media controls made of e-textile sensors in contrast to multitouch screen-based interaction.

The three main contributions of this paper are:

- Designing three fabric-based sensors for wireless media control designed to fit seamlessly within the interior design of the car.
- Presenting the first user study evaluating textile-based sensors embedded in the car interior for ubiquitous non-driving interactions and discussing both qualitative insights and quantitative results.
- Comparing and analyzing the user experience of textile-based sensors versus screen-based interaction and presenting future design opportunities based on both our results and prior literature.

2 RELATED WORK

This paper is situated at the intersection of Human-Vehicle Interaction (HVI) and e-textile fabrication methods. In the automotive industry, women are underrepresented worldwide [18, 49, 67]. Accordingly, the user interfaces designed for in-car interactions are influenced more by those perspectives. On the other hand, the textile disciplines in general—including the e-textile area of research—has more female representation, influenced in part by the historical marginalization of women towards sewing and related fields seen as a more female-suitable discipline [90]. This suggests the current lack of, and the critical need and opportunity for, more inclusion in the area of HVI for a richer design space.

Bridging the fields of automotive design and e-textiles was challenging due to the ways that design thinking in these two fields varies significantly. For example, in the automotive field, button interfaces are preferred for different functions, and utilitarian aspects dominate [17, 41], taking a machine-operation orientation rather than a focus on the lived experience. In contrast, in e-textiles aesthetic and experiential aspects are as important as functional aspects [94]. Not surprisingly, because of these differences, there is a lack of prior work on e-textiles for in-car interactions for the HCI community to build on. Most of the research on e-textiles is oriented towards wearables, and e-textiles for non-wearable fabric surfaces are still mostly under explored [77, 84]. Therefore, there is a gap in designing and implementing e-textile sensors for in-car textile surfaces to be embedded seamlessly into the car fabric, that match the interior, and operate reliably.

In reviewing the literature we should also note that this research area is further complicated by the proprietary nature of automotive research, which is a major challenge to this field of research and makes it harder to build off of previous work [48]. As a result, in this review we can only access the limited publicly-available research.

2.1 Interaction Modalities in HVI

Prior research in the field of HVI often focuses on *functional* aspects of interaction and developing interfaces to enable different NDRAs and DRAs (driving-related activities) within vehicles—with a focus on maintaining safety [8, 109]. Some HVI studies developed Voice User Interfaces (VUI) for cars, including their use to control in-car visible objects (e.g. mirrors, windows) by saying their name and desired function [98]. Others used voice input to control or conduct various activities (e.g. reservations [53], work-related tasks [70], and take-over notifications [61]) with verbal or non-verbal cues [35]. However, VUIs still marginalize people with accents [11], hindering inclusive and seamless interaction. This is a design challenge that needs to be addressed in future work by customizing VUIs to different pronunciations combined with varied emphasis [11] and furthermore to their identity [13], needs, and expectations [11]. Still, there would be situations that require 'silent' interaction modes—alternative to VUI—such as noisy environments or sleeping passengers (particularly young children).

Visual interactions (which can be coupled with audio feedback or set to silent) have become prominent in HVI designs in recent years. In both research and industry, automotive futuristic designs are catching up with sleek button-less all-screen display interactions[1]. Augmented reality enabled screens could be used for external environment interaction (for example, being able to freeze outdoor scenes and share the snapshots later in the role of active passengers [71] or show detailed information of attractions [9] through the rear window for enhanced user experience), games [62] or navigational cues on windshields [12, 129]. Similarly, designers can use lighting in different configurations to tailor in-car interiors to productivity or leisure-related activities for the sake of enriched user experience [99] and inform drivers of various driving-related updates (e.g. speed recommendation [74]).

Previous work has demonstrated how screen-based interaction is focus-demanding [43, 57] and researchers have instead suggested non-distracting tangible interfaces (e.g. tactile touchpad [53] and "*adaptively variable control elements*" [69]) and peripheral haptic interaction for the automotive industry [113]. Prior work has explored tactile interaction for supporting navigation [72] and directional information [56] through a vibrating steering wheel [110], a car seat-cushion [26], and a tactile waist-display [7]. However, these works focused on the quantitative analysis of functional aspects, and user experience and perceived interaction remain a research gap.

Despite the drawbacks of visual and auditory interfaces, emerging automated vehicles (AVs) rely on them in order to revolutionize car interior spaces, with the intention of transforming driving into a side task. Visual and auditory interfaces are widely used for various applications, including driving-related [21], for infotainment [62], and for communicating with pedestrians [68], pedestrians in wheelchair [6], and cyclists [46]. In addition, researchers have explored in-air gestures to control/activate in-car objects [98, 106] and select from menus/lists [53, 66]. Other interaction techniques in the literature include exploring smell interaction with olfactory interfaces as a means of output modality to represent in-car notifications [30, 128], awakening stimuli [34, 89], and evoking feelings [31].

2.2 E-textiles

2.2.1 Non-wearable Textile Surfaces. Prior work in e-textile often overlaps with research into domains such as wearable technology [51, 94, 95] and applications for soft objects and home interiors [15, 80, 81, 96]. However, recent research endeavours indicate that non-wearable textile surfaces are gaining attention. Mlakar et al. [78] investigated embroidered interactive elements on non-wearable textile surfaces to study which patterns and shapes have

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[1] https://appleinsider.com/inside/apple-car

the most tactile recognition and provide design guidelines to assist other designers in designing recognizable e-textile user interfaces. They also examined the impact of different design aspects—visual (shape, colour) and haptic (texture) aspects—for gesture execution on textile UIs by fabricating an array of samples/designs to study how users perceive the visual and haptic affordances [77]. Similarly, Brauner et al. [16] have designed and evaluated an eyes-free e-textile slider as a fabric-based controller for a recliner armchair. Nowak et al. [84] built upon this work and investigated different form factors and tick marks for textile sliders and concluded that raised and recessed sliders provide better recognition and guidance than flat closed-shape sliders. Researchers are also increasingly exploring the possibilities for combining embroidery with other processes such as embroidering PCB components in place [39, 47] or combining embroidery with 3D printing [38, 40].

2.2.2 Fabrication Methods. There are a wide variety of methods used for integrating conductive threads or yarns with non-conductive threads, such as manual sewing or using embroidery [47], weaving [102, 117], and knitting machines [23]. As HCI expanded more into materiality, we see conductive threads incorporated into conventional textiles or transform the textile into a conductive fabric. The first method is the coating method, in which non-conductive thread is coated with metals, galvanic substances or metallic salts to be conductive. Electroless plating [63] and a conductive polymer coating [45, 105] are the common processes of coating. Another popular method is stamping/printing conductive inks to have conductive lines on textile substrates, which have low process complexity [37].

Advancements in different kinds of e-textile input sensors, such as pressure-sensitive textile sensors [93], conductive threads and fabrics [101], and advanced fabrication methods [115], make e-textiles more feasible for a wide range of applications. Parzer et al. [93] investigated detecting surface and deformation gestures such as twisting, folding, pushing and stretching on the sleeve by leveraging conductive threads woven into non-conductive fabrics in the top and bottom layers and pressure-sensitive fabric in the middle layer. With conductive cloth, Ono et al. [87] fabricated a flexible and lightweight touch-sensitive fabric touchpad that detects XY coordinates of hand positions. The touchpad was then applied and mounted on conventional clothing (i.e. a jacket cuff) for controlling the sound of a media player [87]. The method used for fabrication is said be low cost and easier to make than prior work [101] but we did not find it easily replicable. Another example of incorporating e-textiles using conductive threads into a piece of clothing is Karrer et al.'s work [55], which designed an eyes-free e-textile interface with pinch-and-roll gestures on a user's garment for coarse and fine-grained music player control.

2.3 E-textiles in HVI

Although the fabric interiors of cars provide opportunities for e-textile designers to design textile user interfaces, there is limited work at the intersection of e-textiles and HVI. The existing research on e-textiles for car environments often involves wearables, especially wearable physiological sensors, which collect physiological signals either from jackets [123] or smartwatches or bracelets [20] such as heart rate, galvanic skin response [20] to detect the level of concentration of a driver or the of thermal comfort of each individual so that the in-car climate can be adapted to passengers accordingly [123]. Bio-sensing interfaces or pressure sensors were also proposed to be integrated into the car interior, such as seats, steering wheel, and seat-belt, to detect ECG, EDA signals and breathing level of a driver [124], or different sitting postures [75].

Regarding in-vehicle interactions, Nanjappan et al. [83] have designed and implemented a fabric-based wearable device for the wrist to conduct non-driving related activities related to phones, navigation maps, and music players either on the steering wheel, off the steering wheel or on the gear shift. However, there is preliminary work that proposed non-wearable in-car textile surfaces. This work is limited to the BMW Shy Tech concept [3], a poster [59], and a demo [32] of an e-textile interface for cars but without reported results of a user study. Therefore, leveraging the textile surfaces of vehicle interiors for in-car interactions is yet to be explored.

3 DESIGN AND PROTOTYPING

Inspired by previous work in e-textiles (for the aesthetic aspect of prototypes) [16, 77] and motivated to extend HVI literature into an under-explored area, we embarked on a journey to design e-textile sensors for NDRAs.

3.1 Design Concept and Rationale

To cover the research gap highlighted above, our goal was to design aesthetic interactions and materiality for a richer user experience as opposed to the functional utility for increased productivity. With this aim, we focused on media interactions (such as using audio players) as an example of non-driving activities that contribute to pleasurable experiences in the car. Controlling an audio player while driving serves as one of the common NDRAs that is nowadays carried out through BYOD (e.g. mobile phones) or screen-based interfaces installed/integrated on/in the dashboard due to the direction most car companies such as Tesla are taking in their designs [112, 121]. This application is pervasive in daily life (i.e. most people are familiar with media players in their cars), which facilitates replication and comparison with other e-textile fabrication methods [78, 92, 122] and studies [86]. Accordingly, we aimed to study our e-textile sensors against such screen-based interfaces in terms of user experience and distraction (measured with glance off the road duration). With this goal, we specified the design constraints to focus on a subset of essential controls that are achievable to design within all limitations, i.e. i) play and pause, ii) changing the volume up and down, and iii) choosing the next and the previous soundtrack (forward and backward).

3.2 Design Decisions and Considerations

Since the design rationale was to augment the textile areas around the driver's seat for ubiquitous interactions, we resorted to embedding the interactivity within the areas covering the steering wheel, seat-belt, and headrest (given the configuration of the vehicle simulator utilized for, and the exploratory nature of this study). The decision to limit the design constraints as such was aimed to 1) assign each e-textile sensor to one of the mentioned areas for only one purpose, and 2) gain insight on a range of user experiences while users interact *in front of* them within the normal range of

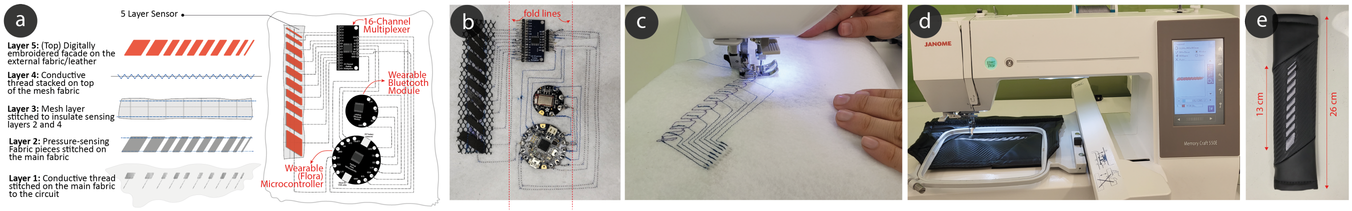

Figure 2: The fabrication process of the interactive seat-belt pad: a) an illustration of the 5-layer slide-sensor circuit; b) a photo of the fabricated circuit; c) machine-sewing conductive thread for Layer-1 of the sensor; d) digital-embroidery of Layer-5 on the (flat) seat-belt pad; and e) the final prototype of the (folded) seat-belt pad.

sight (i.e. steering wheel), *on-body* (i.e. seat-belt), and *behind* them (i.e. seat headrest). To avoid unintentional interactions in the aforementioned areas, the user input method has to avoid using simple touch or capacitive sensing (due to its limitation to sense a wide field in a very close vicinity, not a specific area [42]). Therefore, we designed more complex interactions such as double-tap, long bi-directional swipe, and head gestures using resistive sensing to accommodate the nature of textile surfaces around the car that are frequently handled and come in contact with the user's hands.

Following extensive experimentation, testing, and pilot evaluation, we developed three prototypes to elicit users' experiences regarding interactions with e-textiles for NDRAs while driving. We designed our prototypes as embedded interfaces within in-car accessories (i.e. seat-belt pad, steering wheel cover and headrest cover). Each prototype was portable, independent, wireless, and removable. In addition, any dangling wires or power cables need to be eliminated and replaced with a removable rechargeable battery that we integrated into the internal body of each design. Similarly, we implemented wireless connectivity through Bluetooth communication between the e-textile sensors and the media system.

3.3 Sensor Design and Fabrication Method

Our method of fabricating different sensors for our three designed prototypes was based on e-textile resistive sensing [60] using a 5-step process (see Figures 2 to 4):

Layer 1. Intended row of solderable conductive threads (e.g. Karl-Grimm) are stitched on the base felt fabric. Conductive threads are connected through 16-channel multiplexers (when using more than six pins) to Arduino-compatible microcontroller input analog pins.

Layer 2. Afterwards, pieces of piezo-resistive black fabrics are attached on the conductive threads (in Layer 1) for pressure sensing—either through stitching or adhering using iron-on adhesives—based on the intended design (it could be a grid of 8×8) or a column of 11 or 6 electrodes).

Layer 3. A polyester hexagonal black mesh fabric—through stitching or adhering using iron-on adhesives by the sides—is attached over the bottom layer to make space between the top conductive thread and bottom layer to enable pressure sensing capability.

Layer 4. One or a row of conductive threads/strips (for a grid) needs to be adhered using an iron-on adhesive or stitched to the mesh fabric (at the right angle to the conductive threads used in Layer 1), being placed over piezo-resistive fabrics. In addition, they should be connected through 16-channel multiplexers (if more than six pins are used) to the Arduino-Compatible micro-controller output digital pins. The pressure sensing is activated when the top conductive thread comes into contact with the piezo-resistive fabrics. Based on the amount of pressure applied to the piezo-resistive fabrics, the values range from 0 (maximum pressure applied) to 1024 (zero pressure applied).

Layer 5. The last layer is the design's aesthetic aspect (visual and texture). The aesthetic layer fabricated will be added on top of all the layers to afford gestures visually and tangibly. For this project, we used embroidery (employing Janome embroidery machine[2]) for the last step for seat-belt and steering wheel prototypes since this technique is commonly used for in-car interiors. This last and external-facing layer (which the users perceive as the sensor interface) is recommended to be a leather or fabric material that matches the rest of the car interior in colour, gloss, and texture. The embroidery pattern can be designed using Adobe Illustrator and digitally embroidered for an aesthetically appealing look. Thicker or shiny embroidery thread can be used to emphasize the tactility and seamfulness of the sensing area for ease of use and eye-free interaction. Fray-free threads are recommended to sustain a longer lifespan of user-touch interaction. Recent work [77, 78] explored potential design and their associated visual and physical affordance with respect to the intended gesture or hand manipulation. We inspired their design ([78], Figure 2.27, p. 1168) for sliding and their later design ([77], Figure 9, p. 6) for tapping interactions.

3.4 Prototypes

Regarding the fabrication of our three prototypes, we adapted off-the-shelf vehicle textile accessories and embroidered them with e-textile sensors for our study.

3.4.1 *Seat-belt.*

Our first prototype was fabricated using a seat-belt pad (when spread out 21×26 cm (W×L) and when folded 8×26 cm (W×L)) made out of faux black leather externally and a padding foam layer (for comfort) internally, see Figure 2. The seat-belt area is close to the driver's body; and thus, they can use minimal hand movement and effort to interact with that region. The gesture we used for the seat-belt pad interaction is the vertical bi-directional swiping gesture (i.e. up and down), as it matches the physical properties of the seat-belt pad being long and narrow. With each swipe, the volume would increase (swipe up) or decrease (swipe down) by

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[2] https://www.janome.com/machines/embroidery/memory-craft-550e/

Figure 3: The fabrication process of the interactive steering wheel cover: a) an illustration of the circuit showing the 5-layer double-tap sensor; b) digital-embroidery of Layer-5 on the (flat) steering wheel cover; and c) the final prototype of the (rolled) steering wheel cover.

25%. We machine-sewed the circuit using conductive thread and digitally embroidered the sensor with 11 touchpoints to recognize the full swipe interactions versus accidental touch. To embed the fabric circuit inside the seat-belt pad, we cut the internal foam of the pad and attached the fabric circuit using felt on the inside of the pad. The prototype was implemented using a wearable Flora microcontroller (powered by a rechargeable 3.7V LiPo battery) connected to a 16-channel multiplexer for managing the multitouch input and a compatible Flora Bluefruit module for Bluetooth connection.

3.4.2 Steering wheel. The second prototype was fabricated using a steering wheel cover made out of faux black leather, with a width of 9 cm when it is flattened; see Figure 3. We selected the double-tap gesture—to avoid inadvertent activations while turning the steering wheel—for pause/play media input to be performed on the top half of the steering wheel cover. This decision was based off of prior work [125] that found hand positions on the top half let users have the most control over the driving situations and our observation of drivers holding the steering wheel from the top half. We designed and digitally embroidered right and left-facing arrow shapes using silver thread—with dimensions of 2×2.5 cm (W×L) and being 14 cm apart from each other—for the aesthetic layer of the steering wheel sensors as they corresponded to the standard conventions of the backward and forward media inputs. There are six touchpoints for this prototype, three for the backward and three for the forward inputs points. We implemented this prototype using an Adafruit Feather microcontroller with a built-in Bluetooth module for wireless connection with the media device and connected it to a rechargeable 3.7V LiPo battery.

3.4.3 Headrest. The headrest cover (made out of faux black leather) was used to attach our prototype inside; see Figure 4. For this prototype, we used a grid with a size of 8×8, meaning 64 touchpoints with dimensions of 10.5×12.5cm (W×L). The headrest prototype is used for pause/play media input with the back of the head single tap gesture. For instance, the user hits the headrest with the back of their head to pause the audio track, then hits it again if they wish to play. We programmed it to detect and ignore long presses to avoid pause/play control when the user is just resting their head against the headrest. We implemented this prototype using an Adafruit Feather microcontroller with a built-in Bluetooth module (for wireless connection with the media device) and connected it to 2 16-channel multiplexers (for touchpad control) and a rechargeable 3.7V LiPo battery (for portable power).

4 USER STUDY

To evaluate our prototypes, we ran a user study to examine how users would experience e-textile input interactions while driving in different conditions. We also conducted the same experiment with each participant another time using screen-based interactions to compare the results. During the study, we collected qualitative data through field notes and interviews and quantitative data (as verification of the qualitative result) from the vehicle simulator.

4.1 Method

In an in-person user study, we recruited participants to evaluate our prototypes while driving a vehicle simulator in different scenarios. Three cameras were placed to video-record the interactions from the front (for the seat-belt and eye on the road), side view (for the headrest and steering wheel), and back (for the screen interaction) to ensure all interactions were perceived by the interfaces. The sensors on the steering wheel and headrest automatically registered gestures reliably with connected microcontrollers. However, the seat-belt sensor often glitched during the pilot evaluation (mainly due to the limitations of resistive sensing on non-flat surfaces [76]), causing signal disruption when sensors are bent), in which case we employed the Wizard-of-Oz (WoZ) method [25] by remotely controlling the volume timely according to user input on the seat-belt pad (observed by the wizard constantly during experiments on the monitor behind the participant) to maintain a realistic experience. Participants did not notice any wizard action and reported their reflections normally. Since interaction time was out of the study scope and only GORD (Glance Off Road Duration) [4] was measured in our quantitative analysis, WoZ did not affect the results.

To compare e-textiles to direct screen-based interactions, our method included repeating the experiment with a smartphone (Samsung Galaxy S7 Edge running on Android OS) on a vent-mount holder for all scenarios; see Figure 5. Both fabric-based and screen-based inputs were used to control the same set of audio-based media interactions (on Spotify). Our method for qualitative data collection included documenting field observations and handwritten notes while participants were driving and interacting with our prototypes and audio-recording pre and post-study interviews to elicit their experiences. For quantitative data, we collected the speed as a driving performance measure from the vehicle simulator and video-recording to analyze the Glance Off Road Duration (GORD)—glances either at the phone screen or the e-textile sensors—for each interaction in both scenarios.

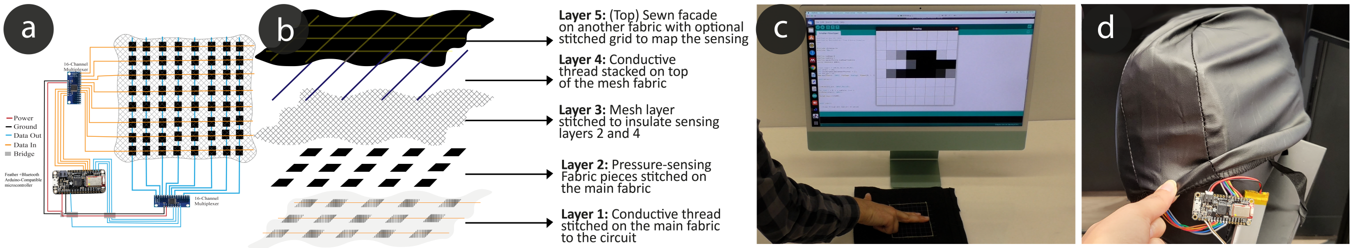

Figure 4: The fabrication process of the interactive headrest cover: a) an illustration of the circuit showing b) the 5-layer multi-touch sensor; c) programming the multi-touch sensing input; and d) stacking the touchpad sensor circuit (hidden) inside the headrest cover.

4.2 Study Setup

The study was conducted in a lab setting using the vehicle simulator system VS500M[3] (see Figure 6). The simulator system (with tactile and tangible driving controls) ensured the safety of participants on the (virtual) road. The simulator also enabled various driving environments, scenarios, times of day, and weather conditions we programmed and fixed for all participants to be a 'sunny morning' as independent variables. For the driving scenarios, we chose two modes representing busy traffic 'in the city' and speeding ahead 'on the highway' (i.e. expressway) to broaden our collected data and understand how e-textiles can benefit users in different conditions.

The vehicle simulator consists of three displays providing a 180-degree front view and a front camera installed on the middle display to capture interactions. The vehicle simulator graphics were processed and rendered by five servers placed in the server rack cabinet; each was responsible for one of the five displays at the front and rear. The observer also would stand near the server rack cabinet and monitor the driving scenarios through the control station. Our interview questions revolved around: 1) what are your current experience and main challenges with audio-player interactions in the car (pre-study)? and 2) how did you find the fabric sensors compared to the multi-touch screen in terms of design qualities and usability factors (post-study)?

Figure 5: Final implemented prototypes (right) versus the touchscreen interaction through the smartphone (left) when each is situated on the driving vehicle simulator.

4.3 Participants

A total of 16 participants (9 females and 7 males) were recruited—in line with the sample size of previous work [19]—for the study through circulating recruitment letters via email among our institution's students and snowballing to local residents (see demographics in Table 1). Participants ages range from 18 to 40 (mean=24.43, SD=4.92). In addition, they are from diverse ethnic backgrounds—East and South Asia (4), Middle East (9), and North America (3)—that support a wide range of different driving styles. Our recruitment criteria excluded individuals with less than one year of driving experience to ensure that the results are not impacted by other factors related to the driving learning curve. We selected participants from different ethnic backgrounds and genders to diversify the collected data and broaden its validity. Analyzing the qualitative experience derived from such a diverse group also enriches our understanding of how e-textiles could be embedded in the HVI design space.

ID	Age	Gender	Background	Years of Driving	Traffic Familiarity
P1	27	W	Middle East	9	Right
P2	20	M	Middle East	1	Left
P3	21	W	North America	1	Right
P4	20	W	East Asia	2	Right
P5	27	W	Middle East	9	Right
P6	18	M	East Asia	1	Right
P7	40	M	Middle East	22	Right
P8	26	M	South Asia	6	Left
P9	27	M	Middle East	5	Right
P10	20	M	South Asia	1	Right
P11	25	W	Middle East	6	Right
P12	23	W	Middle East	1	Right
P13	25	W	North America	9	Right
P14	26	W	Middle East	8	Right
P15	22	M	North America	6	Right
P16	24	W	Middle East	6	Right

Table 1: Participants' demographics

Ethical approval was obtained from our institutions ethic's board. As our study was conducted in person during the COVID-19 pandemic, we adhered to the health protocols, including sanitizing all the equipment after each participant finished the study and mask-wearing during the whole study to ensure the safety and health of our participants.

4.4 Study Design and Driving Scenarios

Between the pre and post-study interviews, participants were requested to start the experiment (approximately 35 minutes of driving in total) with four phases, see Figure 7. The first phase was intended for 'adaptation', where participants familiarized themselves

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[3] https://viragesimulation.com/

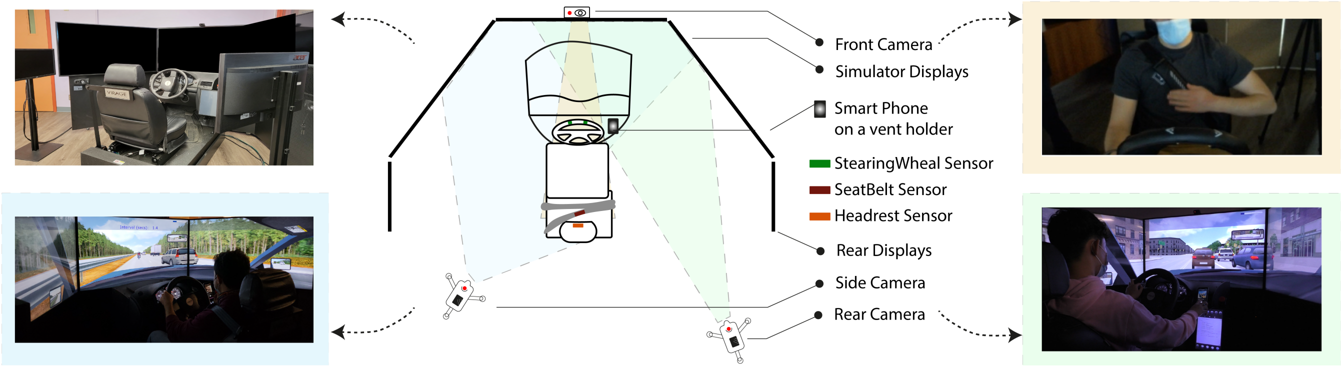
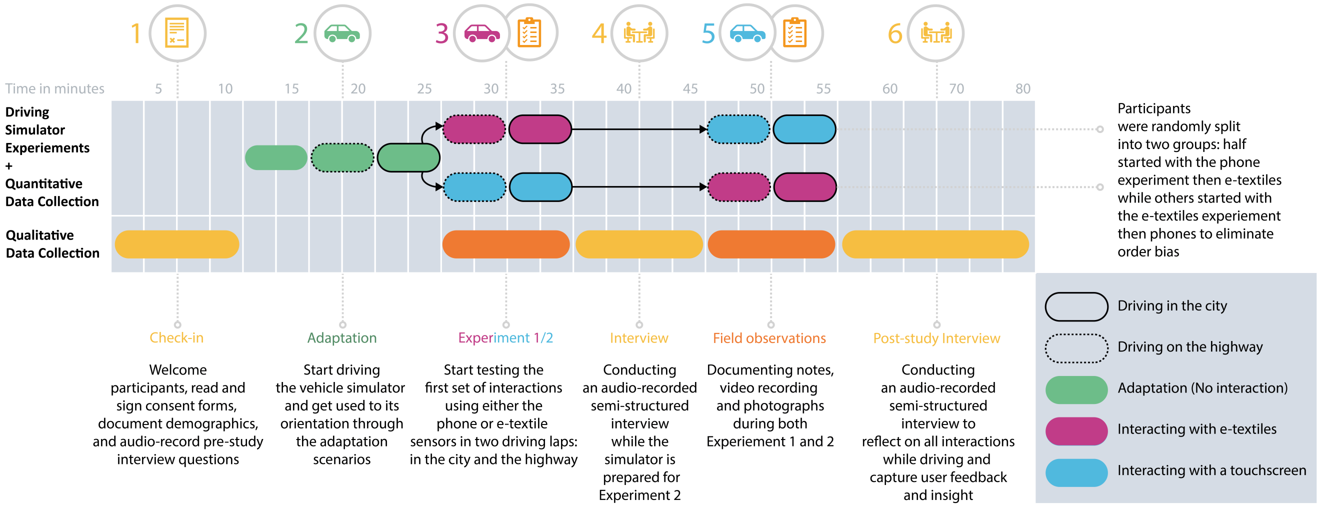


Figure 6: The lab setting where the vehicle simulator is situated and the three angles where the front, side and rear cameras captured participants' interaction with the designed sensors.



Participants were randomly split into two groups: half started with the phone experiment then e-textiles while others started with the e-textiles experiement then phones to eliminate order bias

Welcome participants, read and sign consent forms, document demographics, and audio-record pre-study interview questions

Start driving the vehicle simulator and get used to its orientation through the adaptation scenarios

Start testing the first set of interactions using either the phone or e-textile sensors in two driving laps: in the city and the highway

Conducting an audio-recorded semi-structured interview while the simulator is prepared for Experiment 2

Documenting notes, video recording and photographs during both Experiement 1 and 2

Conducting an audio-recorded semi-structured interview to reflect on all interactions while driving and capture user feedback and insight

Figure 7: The study design timeline showing different driving scenarios and the order of sensor interaction.

with the vehicle simulator and the immersive physical environment. This adaptation phase required about 15 minutes in total: 5 minutes for adjusting to the environment, 5 minutes for adapting to the first scenario (i.e. expressway setting), and 5 minutes for the second scenario (i.e. city setting), see Figure 8. The second phase of the experiment was comprised of two driving laps/runs, 5 minutes each, where the user's interactions were observed and recorded. The two driving runs are for the two scenarios: the expressway (where users are instructed to preserve their lane in a straight line and fast speed by keeping a three/four-second gap from the front car in light traffic); and the city scenario (with numerous red lights, turnings, and moderate traffic). In addition, the two scenarios were repeated across all participants in the same order–first the expressway scenario and then the city scenario. The third phase was about 10 minutes, where participants stepped out of the simulator to reduce any potential motion sickness effect while a research team member prepared the simulator for the second experiment. This phase was also used to cover some of the interview questions on the immediate impressions of participants. The fourth phase was similar in design to the second phase except with the screen interaction if the participant had started with the fabric interaction or vice versa. As a crucial dependent variable, and to avoid order effect, we changed the order of the screen-based and fabric-based interactions per participant, where half started with fabric sensors, while the rest started with screen interaction.

Prior to the study, each participant shared their favourite playlist (containing 10 to 15 audio tracks) to use for their personal media interaction experience. During both experiments, we would turn the lab lights off to create a more immersive driving experience for participants, who would then only focus on/within the simulator. Participants were not instructed when to interact or the frequency of interactions with screen/e-textile sensors to avoid hindering their smooth and genuine experience of their usual driving. Participants were told to control three inputs to the media player (i.e. Pause/Play,

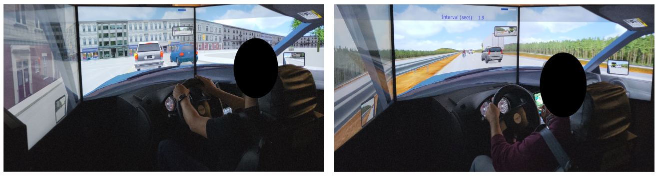


Figure 8: The two scenarios, i.e. city and expressway, were used for the e-textiles and screen-based interactions during the study. The left figure shows the city scenario where the participant is interacting with the steering wheel sensor, while the right figure shows the expressway scenario where the participant is interacting with the multitouch screen.

Volume Up/Down, and Forward/Backward) at their convenience. We note that the gear shift was automatic, and users were only in charge of the longitudinal and lateral control (SAE level 0,1,2).

4.5 Analysis

In this project, we conducted both quantitative and qualitative data analysis. By analyzing the video recording of all participants' interactions (with both e-textiles and screen interaction) from three different angles (see Figure 6), we were able to calculate the total number of interactions with each input per participant in addition to their Glance Off Road Duration (GORD) from reviewing the time-stamped recordings. Afterwards, we ran a three-way ANOVA test to examine any effect of the three factors: the *scenario* (city, expressway), the *input* (pause/play, forward/backward, volume up/down) and the *interaction modality* (e-textiles, screen) on the driving behaviour (speed variance around the interaction) and GORD. One participant was excluded from the analysis due to recording issues, so the quantitative analysis was conducted for 15 participants.

For qualitative data, we did automated textual transcripts from the collected audio-recorded interviews using Braun and Clarks' approach [14] for reflexive Thematic Analysis (TA) in an iterative process for extracting themes. We used the MaxQDA Software for initial note-taking and then going through the transcripts and making line-by-line iterative codes that aimed to emulate each participant's language. We then brought our codes into a Miro whiteboard, where two authors organized the codes into subthemes and themes to create a narrative map of how individuals reflected on their experience using the sensors and their suggestions and ideas on the next steps.

5 QUANTITATIVE RESULTS

Our conducted quantitative analysis was to verify the qualitative feelings our participants had regarding distraction. In total, we extracted and recorded 400 screen interactions (at least 6 interactions for each scenario per participant) and 559 e-textile interactions (at least 8 interactions for each scenario per participant); see Table 2 and Figure 10. We observed the differences of GORD values per interaction modality and input type ($F_{3,1349} = 16.48$, $P<.001$). Our results show that e-textiles significantly reduced the GORD for all three inputs. For screen interactions, the average GORD of all three inputs is 1.49 seconds, whereas, using e-textiles, this amount has remarkably decreased to an average of 0.37 seconds, which is 302.7% lower eye distraction time than the multitouch screen. In addition, from the interaction number for each input, it can be inferred that the interaction number for the pause/play media input is increased approximately by double, indicating e-textiles have smoothed the interaction for the pause/play media input and enabled drivers to have eye-free interaction with much less visual distractions.

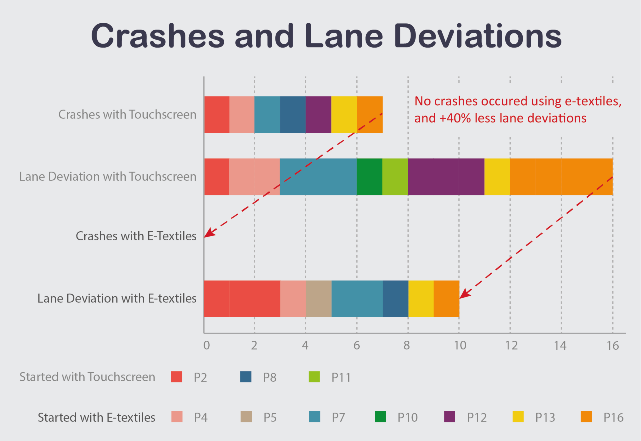


Figure 9: Number of crashes and lane deviations when driving while interacting with multitouch screens and e-textiles.

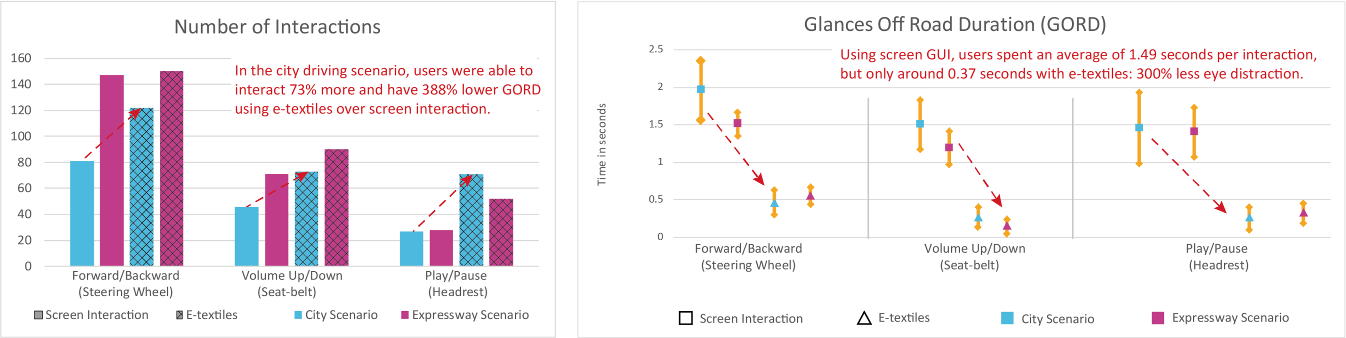
Noticing the reduction of GORD with e-textiles, we assumed that as drivers have more glances off the road with screen interactions, they may also have more speed variance around the interactions, which can be considered risky driving behaviour. Our assumption test relied on calculating speed variance (as our dependent variable) for a 2-second window before and after each interaction and performed a three-way ANOVA to test the effects of different combinations of scenario, input and medium (independent factors) on speed variance around the interaction. We found no significant main effect of interaction of three factors ($scenario \times input \times medium$) on speed variance ($F_{3,1349} = 0.6$, P=.609), nor for the interaction of each two factors, $scenario \times input$ (P=.366), $medium \times scenario$ (P=.37), $input \times medium$ (P=.613). However, medium ($F_{1,1359} = 10.04$, P=.0015) per se had a significant effect on speed variance around the interaction. From this result, we can imply that screen interactions had a significant effect on speed variance around the interaction because of the higher GORD that it required, which results in more lane deviations and crashes to nearby cars. Moreover, participants had 7 crashes and 16 lane deviations with the screen, but zero crashes and 10 lane deviations with e-textiles, see Figure 9.

6 QUALITATIVE FINDINGS

In this section, we discuss the results of our qualitative analysis on how e-textiles affect participants' user experience compared to screen interaction in simulated driving scenarios. Our participants also discussed new opportunities and applications they envision for using e-textiles in vehicles. After finishing the qualitative analysis, we derived several themes, of which (for clarity and space) we discuss the most important three below.

	Pause/Play (Headrest)		Forward/Backward (SteeringWheel)		Volume Up/Down (Seat-belt)	
	N	GORD (±0.05sec)	N	GORD (±0.05sec)	N	GORD (±0.05sec)
Screen-based						
City	27	≈1.45	81	≈1.96	45	≈1.5
Expressway	28	≈1.4	147	≈1.5	72	≈1.19
	∑ = 55	**AVG** ≈ 1.42	∑ = 228	**AVG** ≈ 1.66	∑ = 117	**AVG** ≈ 1.3
E-textiles						
City	71↑	≈0.25 (**↓480%**)	122↑	≈0.46 (**↓326%**)	73↑	≈0.26 (**↓476.9%**)
Expressway	53↑	≈0.32 (**↓337.5%**)	150↑	≈0.55 (**↓172.7%**)	90↑	≈0.14 (**↓750%**)
	∑ = 124	**AVG** ≈ 0.28	∑ = 272	**AVG** ≈ 0.51	∑ = 163	**AVG** ≈ 0.2

Table 2: The table shows the interaction number (N), average Glance Off Road Duration (GORD)—glances either at the phone screen or the e-textile sensors (with an error range of ±0.05 seconds)—for each media input and scenario, as well as how much the average GORD is decreased (shown in percentage) compared to the screen-based interface.



In the city driving scenario, users were able to interact 73% more and have 388% lower GORD using e-textiles over screen interaction.

Using screen GUI, users spent an average of 1.49 seconds per interaction, but only around 0.37 seconds with e-textiles: 300% less eye distraction.

Figure 10: The number of interactions and the average GORD (Glance Off Road Duration) with (min, max) 95% confidence intervals for both screen interactions and e-textiles per media input in each driving scenario (city, expressway).

6.1 Tactility and Physical Affordance

The tactility of e-textiles had a positive impact on how our participants perceived their level of distraction. Overall, our participants perceived a distraction reduction when using e-textiles. In line with previous research [111, 119], our results show that screen-based interactions are not safe—deviating eyes off the road while interacting— and cause extra cognitive workload resulting in imminent accidents. In contrast, e-textiles were perceived by our participants as less distracting compared to screens due to their tactility features facilitating eye-free interactions.

6.1.1 Screens Perceived as Unsafe. Most of our participants (N=10) found screen interactions focus-demanding because they require drivers to take their eyes off the road, which results in distracted driving and safety concerns. P16, P15, P13 and P1 touched upon how small icons on the screen-based interface required precise touch—described as "*fine motor details*" by P15—could lead to distractions. P1 expressed, "*with [screens] not only do I have to press something, I have to check where I'm pressing*", and P13 also noted "*button[s] on the [screen] aren't tactile, so I actually have to look at the [screen] to have an estimate of where the button is*". In addition, P15 mentioned "*vibration of the car and sort of shaking on the car*" as an additional burdensome for touching the screen while driving. Another kind of distraction was notifications that popped up on the screen during driving. P13 described them as "*distracting when I just want to be listening to music and focusing on driving*".

Participants (N=7) elaborated on how these screen distractions can result in accidents or collisions and some expressed that, during screen interactions, they suddenly changed the lanes "*without noticing*" (P1) or lost their "*full attention*" (P7) where they "*could have crashed*" (P1). Half of the participants discussed the cognitive workload of the expressway or city scenarios and how it affected their screen interaction during driving. Some perceived the expressway as "*trickier*" (P1) because of the high speed, keeping a "*certain distance*" (P1) from other cars, and more severe repercussion where "*they could all crash, and the consequences and people [could] die*" (P3). On the other hand, others (P12, P8, P7, P11, P9) discussed how cities are more challenging in terms of screen interactions due to their hectic nature and require high situation awareness. P9 commented: "*In [the] city you need to have more focus on your surroundings and [mentally] requires you to focus on driving*".

6.1.2 E-textiles Kept Eyes on the Road. Most participants (N=14) stated that e-textiles assisted them in better concentration and noticed reducing the need to glance off the road, giving them more control in driving and higher situation awareness. For example, P8 felt that "*[e-textiles] takes probably like 10% of the concentration of what it takes to just look at that particular button in the screen*". P1 stated that the steering wheel sensors did not require taking eyes off the road, and the seat-belt sensors had the capability to "*change volume while turning*" with "*kinda a simple sliding*" (P5). On notifications, several participants highlighted that "*I don't need to worry about it notifying me of a text or a call. I can just focus on the music and driving*" (P13), and that it is especially useful for people who "*are very stressed, and are more distracted*" (P9), giving more control and causing less disruption.

In an emergency or urgent cases, participants (N=5) expressed that e-textiles enable them to react and control media much quicker —"*if something is going on, something urgently comes up in the road, I can switch back to whatever I have to do for the emergency much sooner than while using the [screen]*" (P8). Similarly, P13 commented on the headrest sensor and its feature of hand-free interaction in urgent cases where "*you want to turn off the music when somebody starting to cut you off or you're turning. It's nice to be able to pause, cut the distractions, then as soon as you're done you can like pause or play it again*". Other than urgent cases, our participants expressed that e-textiles increased their situation awareness so that they "*could look at the signs and outside*" (P16) and paying attention to"*what was going on the road*" (P15) while being able to interact with e-textiles, in another sense, being able to "*multitask*" (P13). For instance, in the city scenario, among all the cars, there was an exceptional sports car with a distinct purple colour that was quite recognizable and memorable, programmed to pass by. Some participants highlighted noticing it while interacting with e-textiles, whereas none expressed so during screen interaction.

6.1.3 E-textiles Enabled Tactile Recognition. Half of our participants (9/16) discussed the benefit of tactile features (i.e. the stitch patterns guiding participants on how to interact with them) of the steering wheel and seat-belt. They expressed how it helped them locate the sensors without the need to look at them and appreciated their design qualities. P7 described, "*I like the embroideries, it is like a normal seat-belt with comfortable stitches. That's [how] I know that I am swiping it now, and so I know where to touch*", and P12 noted "*it was great actually. I think [the stitches were] necessary, especially like for the bumps [on the seat-belt], it made me know which direction to go*". The tactility of e-textile sensors assisted participants (P1, P13, P15, P6) in interacting with their media "*without taking eyes off the road*" (P1). P13 expressed they could locate the sensors "*seamlessly*" with the help of stitches "*when turning or changing lanes*" and execute the gesture "*without having to look away from the road*". However, a few others (P5, P8, P7) had critiques of the sensors not being obvious enough e.g. "*I always felt like I have to search for the ones on the top and then I click*" (P5) and P7 requested the sensors be "*more bumped somehow, so I know that's where I swipe [on steering wheel]*". In addition, P8 addressed the same issue for the seat-belt and suggested "*a different touch to it might be better*" or maybe a different texture (P3). Overall, participants had varying thresholds for recognizing the e-textile sensors. Therefore, in the design of e-textile sensors, this feature should be taken into account, either customized or tactile enough for all, so it could be obvious enough for all drivers with, for example, different hand sizes (P13).

6.1.4 Issues with No Visual Feedback. Disadvantages of the designed prototypes included a lack of input confirmation (apart from the audio feedback of the media player), where participants needed further acknowledgement that the input gesture was detected. For example, P16 was confused when the beginning of a song was silent, saying: "*I get confused whether the song is paused due to sensors' error or the silent part of the song is being played*". Sometimes there was a short lag between the time sensors activated and the time commands being sent to the audio system (caused by technical issues with the driving simulator). This prompted participants (N=2) to wait for a second "*to see if it actually happened or did I miss it, or was it powerful enough?*" (P1). Accordingly, P1 and P5 suggested visual elements to be integrated into e-textile UIs, "*like a slider that would fill up or down based on the volume value*". Another issue with relying only on auditory feedback was understanding volume ranges when interacting with the seat-belt sensors. Some (4/16) had difficulty with non-visual scales, e.g. P8 stated, "*if I swipe up or down I cannot understand how much the volume is increasing or to what extent the volume is changing*". To resolve this problem of the "*range of loudness*" (P15), P3 suggested designing the sensors in a way that the min and max values are recognizable and attainable. Finally, participants recommended further media functions such as navigation flexibility to enable moving to and playing multiple songs back or ahead (P12).

6.2 Novelty Factors and Learning Curve

Most participants (90%) during the briefing of the study expressed that it was their first time hearing about e-textiles—"*it's kind of new. I haven't seen such thing with fabric, I hadn't any experience with that*" (P16). Accordingly, they were unsure "*if it's going to be feasible or practical*" (P5) due to a lack of familiarity. This is understandable since e-textile research began just over 20 years ago in academia and less than ten years ago in industry [100]. Therefore, it is a new domain for consumers and "*not mainstream yet*" (P15).

6.2.1 Initial Shallow Learning Curve. As new technology emerges, "*there's going to be a bit of inertia*" (P15) for people to change over from previous technologies to the newest technology. The learning curve for adapting to e-textiles from current in-car technologies was discussed by several participants (6/16). Some still prefer screens (P13), voice (P9), and buttons on the steering wheel (P2, P10) while all other participants (12/16) preferred e-textile sensors. P10 gave an analogy for that learning curve, comparing it to people changing from old push-button phones to touchscreens —after getting used to it "*your thumb just remembers how to do stuff*". Moreover, P5 noted that the learning curve to adapt to the buttons on the steering wheel could be the same for e-textiles; "*maybe the first month I was like where am I clicking?...so it could be the same with textiles*". Initially, while interacting with fabric-based sensors, "*you have to learn all these new things*" (P10) and memorize the gestures and locations. But "*after a point of time it becomes very mechanical that people will effortlessly keep on using it*" (P8). P15 added "*once you get more used to it, then you'll get better at it, obviously. On my last turn, I was feeling like I was doing a lot better than on my first turn*".

6.2.2 Utilizing Muscle-Memory. From our findings, the preference for sensors and gestures highly depended on whether participants had formed muscle memory with that location or not. For example, four participants conceived the seat-belt sensors as "*really intuitive* (P13) as they could easily rub their finger on the seat-belt "*to turn up and down the music*" (P14) and "*shape of the seat-belt lends itself* *to that swiping motion*" (P13). Therefore, if they wanted to turn the volume up, they would just move their hand upwards as expected (P12). P4 also stated that the seat-belt gesture was familiar as they would "*stroke the seat-belt to make sure it's flat*" and not "*twisted or rolled around*". Muscle memory with headrest sensors and steering wheel sensors were also evident in comments. P6 described steering wheel sensors as "*pretty convenient, simple, and straightforward*, and P12 mentioned interacting with the headrest sensor is like "*leaning back my head*", so it is convenient to interact with.

On the other hand, some participants (N=6) hadn't formed muscle memory with the e-textile locations. They stated that the headrest gesture is not a "*natural motion*" (P15) as normally you have your head in a constant position and it "*doesn't touch the headrest*" (P11). Apart from the headrest, other participants discussed how they were not used to seat-belt and steering wheel sensors. P12 diverged from the other participants when discussing the seat-belts sensors and considered seat-belt e-textile sensors as "*kind of unnatural*", as they are not used to interacting with seat-belts while driving. P16 and P7 disliked the sensors being on top of the steering wheel as their style for holding the wheel differs from the placement of our e-textile sensors. As drivers have different habits of holding the steering wheel, some participants (N=3) suggested "*customizable placement of sensors*" (P13) based on drivers' style of holding the steering wheel.

6.2.3 Designed for the Car. Participants reflected on how phones are not designed for the car such that the driver needs to search and find the media functions they intend to activate during a ride, which makes them distracted as well. Although some recent car models have built-in car audio player controls, they come at a high price and need the entire car to be purchased. However, participants perceived the e-textile accessories that can retrofit any existing car model as "*designed for the car*" (P3) and without needing "*to remember anything*" (P5) supporting "*smooth access*" (P11) to these interactions.

6.3 Dimensions and Reachability

Participants requested easy-to-reach locations and a bigger interaction area for e-textile sensors. Our participants also discussed the challenges that very easy-to-reach locations could pose to the driver, requiring designers/researchers to offer better solutions to prevent accidental activation of sensors.

6.3.1 Bigger is Better. Commenting on the perceived size and dimensions of the e-textile sensors, most participants (75%) were happy, while some wanted bigger interaction areas where "*anywhere in the bottom side [of steering wheel] you click, it can go to next song*" (P8). P6 and P1 noted, "*I have to check or touch it to make sure that I'm pressing the right spot*" (P1), "*so if it's wider it'd be better*" (P6). For the seat-belt sensor, participants found it helpful to be bigger. P12 commented, "*the area in which I [swipe] is quite large, which is pretty much needed. I don't have to focus on a single spot where I need to click*", and P8 stated: "*I can swipe any part [on the pad] to move the volume up or down*". This reiterates the notion that users do not want to divide their attention on finding the right spot for sensor activation. Therefore, the design dimensions are crucial for quicker and less distracted interaction.

6.3.2 Within-Reach Convenience. Participants discussed the proximity of e-textile sensors. While driving, it is vital to have "*the easiest connection possible to things*" (P10). As E-textile sensors are "*closer to the driver*" (P4), it has made the media interactions "*within reach of your hand and easily accessible*" (P1) compared to reaching for the screen. P14 mentioned the reason by saying: "*they're already on the wheel or it's on your seat-belt, or it's on the back of your head, so you don't need to move your hand that much, so it doesn't distract you*". In addition, with these easy-to-reach e-textile sensors, "*you can make a faster change on textiles, so we can make a sudden change*" (P5) with "*less latency*" (P10) and "*small movements*" (P13), creating more control over media inputs (e.g. "*could change volume while turning*" (P12)). Small and fast movements through e-textile sensors benefit drivers because they don't need to take their hand off the steering wheel (P13)—"*only move my thumb*" (P10) —and they can have their eyesight on the road (P12); as a result "*not pulling your distraction from looking at the screen*" (P13) and helping you to be focused on the road (P1). Commenting on which hand to use with different e-textile sensors, P8 expressed that "*in almost every circumstance you can use any hand for that, right or left doesn't matter. It's always in reach*". Similarly, P11 felt that "*the seat-belt is a perfect idea as it's close to your body*" while the headrest "*does not require any hand movements*".

6.3.3 Other Easy-to-reach Locations. In reference to other "easy-to-reach" locations, four participants suggested the bottom of the steering wheel, and two proposed the sides. In addition, the "*inner curve of the wheel* (P7) with swipe gesture, "*back of the wheel*" (P7, P5), and the center of the steering wheel (P4) were also recommended. These locations were influenced by the interference of touching the sensors while turning (e.g. "*when you're turning, you're always grabbing like that part*" (P3)). Other locations included the area near the gearshift (N=5), door panel (N=5), and armrest (N=4). Other interesting design recommendations included: "*the ceiling of the car*" (P12) for turning on the light and leg gestures (instead of hand gestures) on the carpet for window and chair angle control (P5, P11). Easy-to-reach locations were also proposed for passengers "*on the backside of the front seats*" (P14, P16).

6.3.4 Challenges with E-textile Interactions. Despite the easy-to-reach advantages, some participants (N=6) discussed challenges in the case of a manual gear shift (where one hand is typically moving between the steering wheel and the gear) and when taking many turnings (in the city) as users can't interact with steering wheel sensors while "*moving your wheel*" (P6). Other concerns with seat-belt sensors in the expressway were due to the fast speed and being close to other cars; as P14 commented "*when I wanted to rub the sensor on the seat-belt, I kind of got nervous that I could lose control*". While some suggested the integration of all sensors on the steering wheel (N=4) where "*everything is under your fingertips*" (P5), others (N=3) preferred moving all the controls to the seat-belt to avoid false activation on the steering wheel and for easier access to all the sensors while doing turns (P13). Since participants had different preferences, the separation or integration of sensors can be customized for different users based on their perception of easy-to-reach locations.

7 DISCUSSION

This exploratory study investigated e-textile sensors for NDRAs, i.e. media interactions. Although results show that e-textiles are perceived as less distracting and reflect lower GORD (Glance Off Road Duration) compared to the screen-based UI, we do not claim any superiority of our e-textile sensors over buttons and how e-textiles are compared to them, as the comparison was solely between e-textiles and a screen-based interface due to the growing interest in designing more screen-based apps for in-car GUI. The comparison between buttons, e-textiles, and screen-based UIs is something to be explored and investigated in future studies. This section discusses the future vision for these interfaces and how they could be designed based on current research trends and trajectories. Our work triggers a more critical reflection on the current trajectory of vehicle interior design for vehicles in terms of integrating e-textiles.

7.1 Overall Reflection

Expanding the Design Space. To benefit from the advantages of e-textiles in the area of automotive design, car interiors could need to change to be tailored to the needs of individual passengers and drivers. However, there is limited research investigating how to redesign human-driven cars' interiors to a more personalized, tailored environment for different NDRAs, including media interactions. There are also tensions around changing current design patterns, such as the safety of individuals 'borrowing' or temporarily using someone else's vehicle. However, with the introduced notion of designing fully-interactive and wireless fabric-based sensors as accessories (such as add-on covers and pads), the design space can witness the rise of numerous designs that act as on-demand add-ons independent of the car model or features. These accessible add-on accessories can be added to existing cars without waiting for the automotive industry to make dramatic changes in the interior of their fancy new car models to incorporate those designs.

Empowering More Target Users. As we progress towards the integration of ubiquitous computing in the car interior, car interior design will be subject to significant changes and reorientation towards passenger-centric interactions [114]. Recent research directions point toward future car designs that will vary from the current human-driven cars, bringing new opportunities for unprecedented NDRAs [108, 117]. In the near future, cars' interiors could be transformed into tiny houses or living spaces [28, 114] where all the materials and objects could be interactive with on-demand NDRA interactions done seamlessly. This new paradigm of in-car interior interactive fabrics creates the potential for expanding the 'tiny' interior space—limited in the car—and rethinking how to change the car interior to match target users' values, perspectives, activities [114] and the living situations they are used to [88].

Highlighting Design Qualities. Our findings highlight that the area of interaction and placement of sensors play a crucial role in having an effective interactive car interior. When the interaction area is big enough, users are less concerned about which area to touch for sensor activation. Consequently, a wider and bigger interaction area enhances user experience significantly. Along with a bigger interaction area, the reachability of sensors is another crucial factor in an efficient and enjoyable interaction. Small and fast movements for media interactions create a sense of controllability over media inputs and driving, which is realizable by having e-textiles in easy-to-reach locations. Most participants considered the locations we had designed e-textile sensors for as easy-to-reach locations, non-wearable e-textiles around the body: in front of (steering wheel), on-body (seat-belt), and behind (headrest), which opens up new opportunities for further research in the realization of other NDRAs with e-textiles, not only for drivers but, more importantly for passengers.

E-textiles and Tactile Features. Participants had the impression e-textile sensors enabled them to execute intuitive gestures without being distracted substantially while on the drive, and this was also verified in our quantitative results. We have designed the steering wheel and seat-belt e-textile sensors to be simple in shape and to communicate the interaction unambiguously—following Mlakar et al.'s [77] guidelines on textile surfaces—to avoid high cognitive workload. Simple swiping gestures on the seat-belt allowed participants to control the volume even at turnings; otherwise, it would have been so challenging to discreetly change the volume with a phone. Consequently, e-textiles tactility features enabled drivers to be more focused on the road and to pay attention to signs and surroundings, resulted in having high situation awareness of the surrounding environment. Participants appreciated the stitches on the seat-belt and steering wheel, which assisted them in locating the sensors. This finding reflects the first design recommendation (D1) developed by Mlakar et al. [78] on having explicit contrast to the base surface so that users can simply differentiate. Moreover, the stitches afforded the interactions and guided participants on how to execute gestures, which is in line with the fourth resign recommendations (D4) of Mlakar et al.'s work [77], stating that "the shape of an element indicates required interaction". However, some participants wanted more raised or recessed stitches to have higher recognition of the stitches to perform the gesture better accordingly, especially for the increasing stitches of the seat-belt in length to indicate the volume increases or decreases.

Extending Form-factors. Other locations (e.g. armrest, door panel, floor carpets, and ceiling) or integration of all sensors in either the seat-belt or the steering wheel for enhanced interactions were suggested during the study. Exploring these easy-to-reach locations (where participants have formed muscle memory) in future research for designing customized e-textile interfaces is of great importance to be able to reduce the learning curve and, more importantly, increase the acceptance rate of e-textile technology within the car.

Applying Fitts' Law to E-textile. Based on how fast we want a user to reach e-textile sensors in their pod-like environment, we can decide the size and location of e-textile sensors, applying Fitts' law [118] in the design of e-textile sensors. Based on this law, we can infer that the faster interaction with small movements is required, the larger and closer an e-textile sensor should be. However, in future research, this law can be investigated with e-textile sensors in different driving contexts to be confirmed in the 3D space [120] of the car interior.

Supporting Customization. Our sensors' removability and portability features enable us to design customized e-textile sensors aesthetically and in terms of sensor size (for varying thresholds for recognizing sensors) and locations for pod-like seamless interactions. Maybe a car is shared by a family, and different people use that car with different preferences for e-textile sensor design. In this case, e-textile sensors can be designed as car accessories (add-ons) for seamless interaction—which can be removable and replaceable—with different designs for different users.

7.2 Design Opportunities

The results of our user study also present future research opportunities for e-textile interactions and gestures. Moreover, this research allows for expanding on prior work and investigating other input acknowledgment methods.

Novel Interactions and Gestures. Applications of e-textile sensors do not need to be confined to media interactions in our proposed 'pod-like environment'. Based on our participants' comments, they can be designed and used for controlling a wide range of in-car non-driving functions, such as adjusting driver seats, windows, ACs, mirrors, and sunroof. Additionally, these sensors could be applicable for controlling permanent driving functions such as windshield wipers control, cruise control, and indicators. These e-textile sensors can also be designed for other in-car locations with different gestures. Some of the most repeated places mentioned by participants were door panels and armrests. Other locations were the middle of the steering wheel, ceiling and backside of the front seat. Moreover, participants proposed novel gestures. The leg gesture on the mat was one of the new gestures among the other suggested gestures. They suggested the leg gesture be executed on the in-car mat to adjust the windows or seat angle. A squeeze gesture was also proposed for the seat-belt as an alternative for headrest pause/play interaction. To improve the interaction for volume up/down, one of the participants recommended instead of sliding up or down multiple times, when reaching the end of the slider, a hold gesture could be used to adjust the desired volume, which could be designed in future studies on e-textiles for NDRAs.

Novel Functionality and Uses. Pfleging et al. [98] investigated some in-car functions to be manipulated by swiping down/up gestures on display integrated into the middle of the steering wheel. Our e-textile sensors can be a practical alternative interfacefor manipulating in-car functions with less distraction and enhanced user experience due to their capability for seamless, ubiquitous interactions within the car interior. Another work that we believe these e-textile sensors can be used as an alternative—this time for media controls—in a pod-like environment is the work of Berger et al. [10]. They designed tactile control sticks having the same resolution grid as the screens to activate different parts of the screen and choose items with this stick without direct touch. Instead of the tactile stick, our touchpad sensors can be integrated seamlessly into the seat for back seat passengers to activate different screen parts more efficiently.

Input Confirmation Methods. Based on our findings from the first theme (6.1.4), some participants showed hesitation and discomfort in relying solely on auditory feedback for input confirmation. In future research, embedding tactile feedback with different patterns [72, 110] along with visual feedback using light-emitting textiles [5, 24] can be investigated to design some form of multi-modal feedback. Integrating such output into the e-textile sensors is important to acknowledge the input so that the driver becomes assured of the validity of their gesture, creating a richer user experience.

Design Tools for Ideation. During the interviews, when we asked about some of the other opportunities of e-textiles for car interactions, most participants had a hard time ideating different ideas (because of their novelty) and required cues to ideate further. This indicates we need more design tools to help participants facilitate their thoughts during the ideation process. E-textile practitioners have several methods of ideating concepts with participants. One of the design tools can be a swatch book of e-textile samples [44] that can be demonstrated to participants to relate them to the e-textiles field and inspire them with other e-textile samples or applications. It can also be a prototyping toolkit [52] for non-expert users in e-textiles to enable them to make their e-textiles samples for in-car interactions and get better insight into how e-textiles work. Another interesting method is paper-based or online ideation decks to help participants think of scenarios and locations for e-textiles [50]. This method is a promising method to help participants ideate in a more methodological way. All these rich available design tools can be utilized in future work to facilitate the ideation process for e-textile interactions in cars.

7.3 Limitations

There are some limitations to the scope of this research study, namely around the driving simulator, participant demographics, and durability, which we acknowledge in this section.

Durability and Signal Quality. The durability of sensors requires a long-term research study. Since our study's focus was on user experience and usability aspects and we had a time-constrained schedule (enforced by COVID-19 lockdowns), it was not feasible to research and address this matter in a proper manner. As mentioned later regarding the glitches that occurred for one of our e-textile sensors (i.e. the seat-belt) because of limitations of resistive sensing when getting bent while being interacted (causing signal disruption) [76], further research needs to be conducted to resolve the issues on non-flat e-textile interaction in the automotive context and how to maximize their durability.

Vehicle Simulator. We conducted this research in a lab setting (the vehicle simulator) for participants' safety rather than in a real-world environment (actual car). An actual car environment could have included more challenging scenarios—which might have influenced the driver's behaviour differently due to multiple external factors (e.g., road conditions, climate, vehicle's systems performance) [104]. As the vehicle simulator had the configuration for driver user testing, we could not test our sensors for passengers. Among all other driving scenarios, we chose only expressway and city for the sake of animated robustness and limited the weather to sunny (instead of conditions such as rainy, windy, snowing, or night). Moreover, the driving period was limited in each lap of a scenario to 5 minutes to prevent motion sickness or dizziness. Also, the simulator did not have an interactive car-play screen for NDRA/media control, so we used an Android smartphone device mounted on a vent-holder to enable a multi-touch screen-based interaction for a comparative analysis with our e-textile prototypes.

Participant Demographics. Because of time constraints to conduct the study for each participant (≈1.5 hours), we could only include two scenarios of city and expressway (i.e. highway) with a duration of 5 minutes for each to test our e-textile sensors. Due to COVID-19 restrictions, participants were wearing face masks throughout the study, which prevented any facial-expression observations and limited the potential of video analysis of their user experience. For this study, we relied solely on their verbal account or bodily expressions. As the simulator was built for North-American right-hand driving, the interaction with car controls was not entirely standard for everyone. Two of our participants were not accustomed to right-hand driving because they had lived in a left-hand traffic country before. This was one of the limitations that might have impacted the driving experience, accordingly interacting with e-textile sensors. Another limiting factor in the thorough collection of experiences was the demographics of our participants. All of our participants, except for one, were university students with an age range of 18 to 27. Most participants were tech-savvy and knowledgeable about computers. A wider range of participants of different ages and less familiarity with technology could have yielded different results.

8 CONCLUSION

This paper aims to expand the design space of human-vehicle interaction (HVI) and enrich our understanding of user experience by exploring alternatives to current graphical interfaces with interactive interiors [82] and in-person reflections of users. To explore the research gap in using e-textiles in automotive fabric surfaces, we fabricated three e-textile prototypes for car interactions and used them for an example application: i.e. wireless media control. Our non-wearable interfaces were embedded within the steering wheel cover (in front of the user), the seat-belt pad (on-body), and the headrest cover (behind the user's head). After implementation, we carried out a deployment study with 16 participants (9F, 7M) in a driving simulator vehicle environment (to avoid safety concerns of driving an on-road real moving vehicle experiment). Although each participant did the experiment twice (once with e-textiles and once with screen-based interactions), the average number of interactions with e-textiles was significantly higher for all inputs since users felt safer and less distracted as opposed to aiming for on-screen options.

We provided descriptive and analytical accounts of participants' reflections on the physical affordance and tangible interactions with our fabric-based interfaces that focus on different design qualities, proposed enhancements, and reflections on materiality. We analyzed both quantitative data and pre and post-study interviews and reported on findings on user qualitative insights through the top 3 main themes: 1) Tactility and Physical Affordance, 2) Novelty Factors and Learning Curve, and 3) Dimensions and Reachability. We provide detailed and rich insight from participants interacting with novel vehicle interfaces that can reshape automotive technologies in new ways for HVI. Although there is a growing interest in designing more screen-based apps for in-car GUI interfaces and even Sci-Fi interfaces in the car (such as holograms or windshield displays with air gestures), our results align with prior work [33, 111, 119] highlighting their high distraction rate and the low focus on the road. Alternatively, our proposed interaction methods through fabric-based interfaces proved to have 302.7% less GORD than multitouch displays, 60% fewer unintentional lane deviations, and less rate of road accidents and collisions.

Moreover, we detailed the characteristics of our design rationale and prototyping method, building on existing fabrication techniques, that can have great potential when extended by—not only other HCI researchers but also—the maker community. Designing DIY sensors as add-on accessories not only empowers users with accessible means to make their own but can retrofit existing cars with no need to wait for the automotive industry to catch up with expensive new car models.

Additionally, we extend the very-limited interior space inside the car (without introducing a single foreign/additional interface) and utilize the capabilities of the overabundance of textiles in cars as an additional vocabulary for this possible future of interaction. In future work, we seek to overcome current technological constraints (e.g., lack of visual/haptic feedback) to increase usability and iterate the design with further user feedback, leading to automotive deployment in the wild for everyday usage. In conclusion, we aimed to further a mutually beneficial dialogue between HVI and e-textile research areas, bridging the gap between opposite gender-dominated fields, breaking barriers, and *steering* away from the current screen-based HVI direction.

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