Distributing In-Vehicle Interactions Across Devices with Insights into Drivers' Behavior, Preferences, and Usability

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Abstract

Connecting personal devices to the in-vehicle infotainment system has become mainstream in modern vehicles, contouring a distinctive context of use characterized by the user interface being *distributed* across multiple interactive systems, including those in the vehicle and the users' personal digital devices, likely involving different input and output modalities. However, *distributed user interfaces* (DUIs), despite extensively studied in other application domains, have not been addressed to the same extent for in-vehicle interactions. In this context, we examine in-vehicle DUIs and report the results of an exploratory study conducted with twenty-four drivers, who shared their preferences regarding digital device use inside the vehicle. To complement our findings, we also present a demonstrative application featuring a user interface with interaction modalities distributed across the in-vehicle infotainment system and the driver's smartwatch.

CCS Concepts

• **Human-centered computing** → **Ubiquitous and mobile devices**; **Interaction paradigms**.

Keywords

Distributed user interfaces, smart vehicles, V2X, mobile interaction, wearable interaction, cross-device interaction

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1 Introduction

Smart vehicles are increasingly equipped with features designed to enhance driving safety and improve user experience while traveling, providing advantages for both drivers and passengers [27]. In this context, safety features include advanced driver-assistance systems, such as automatic emergency braking, lane-keeping assistance, and adaptive cruise control [13,26], alongside infotainment systems with connectivity options, digital content streaming services, and providing access to interactive applications from the driver's personal digital devices; see Detjen *et al.* [16] for an overview of in-vehicle interaction design and Bilius *et al.* [7] for a formalization of inside-the-vehicle and outside-the-vehicle interactions.

In this context, technological advances involving smart vehicles are encompassed within the Vehicle-to-Everything (V2X) framework [18,23,54], a family of communications concepts, technology, and standards for connected vehicles that specifies data sharing with surrounding entities: other vehicles (V2V), communications networks (V2N), road infrastructure (V2I), and pedestrians (V2P). At the same time, modern interactions with digital devices become increasingly context aware. For instance, DUIs enable interface elements to be spread across multiple devices for multi-user interactions [41]. Therefore, various design options become available by integrating DUIs into connected vehicles and adapting the interface based on drivers' and passengers' preferences and behavior.

Unfortunately, the capabilities of state-of-the-art DUIs have been barely examined for in-vehicle interactions, with the most notable advancement represented by the recent introduction of the Vehicle-to-Distributed UIs (V2DUIs) concept [8], a new member of the V2X family, which leverages the infrastructure of V2X for interfaces that distribute among drivers' digital devices and the in-vehicle infotainment systems. However, this work remains purely conceptual in nature and has yet to be applied or empirically evaluated. In this context, understanding the application potential of DUIs for in-vehicle interactions would benefit V2X goals for increasing driving safety and enhancing travel experiences through adaptive interfaces spanning across personal digital devices and the vehicle. To this end, we build upon the V2DUI concept [8] and adopt the broader perspective of a smart vehicle as a specific instance of a smart environment where users' personal digital devices share data with each other, with services in the cloud, and with the in-vehicle infotainment system, towards a first practical application and user evaluation of V2DUIs. Our contributions are as follows:

(1) We conduct an exploratory study involving twenty-four drivers to understand driving behavior and interactions with personal digital devices. Our findings highlight the frequent use of smartphone and smartwatch functions for listening to music, taking phone calls, and communicating through text messages, with touch being the preferred input technique while driving, whereas voice used to a much lesser extent.
(2) Based on our findings, we developed an interactive prototype and conducted a preliminary usability study of a V2DUI for a music player application, distributed across the in-vehicle infotainment system and the driver's smartwatch.

Our contributions mark the first practical application of the V2DUI concept with empirical results that point to the need for more investigation in this area. We use our findings to propose future work to guide systematic distribution of interface elements and interactions across digital devices within the in-vehicle environment.

2 Related Work

2.1 Distributed User Interfaces

DUIs refer to the distribution of interactive applications across multiple autonomous devices [30] and computers [37], where independent interfaces collaborate, interact, and integrate through network connections [17]. Particularly relevant to the scope of our work are quality properties and models for DUIs, which we apply to the specific context of in-vehicle interactions. For example, Elmqvist [17] considered five defining dimensions across which UI elements can be redirected: *input, output, platform, space*, and *time*, covering pervasive and ubiquitous computing, multi-display environments, and multi-device interactions. Peñalver *et al.* [41] defined four essential properties for DUIs, *portability*, *decomposability*, *simultaneity*, and *continuity*, from which they derived others, such as *multi-platform*, *multi-monitor*, *multi-user*, *consistency*, *flexibility*, and *efficiency*. Ousmer *et al.* [38] examined paired sketching as a collaborative design method for DUIs, involving multiple stakeholders. In relation to a transversal model, Vanderdonckt [51] outlined design principles of DUIs by referring to *tasks*, *users*, *platforms*, and *environments*, *e.g.*, "distribute one/many element(s) of one/many UI(s) in order to support one/many user(s) to carry out one/many task(s) on one/many domain(s) in one/many context(s) of use." This description emphasizes the potential for end users to engage in distributed tasks for efficient completion across various devices, platforms, and environments. To the best of our knowledge, the exploration of state-of-the-art DUI concepts for smart vehicle interactions has been addressed only at a very incipient level [8].

2.2 Inside-the-Vehicle Interactions and V2X

Smart vehicles interact with their internal environment—the driver, passengers, and digital devices [16,27]—as well as the external environment—other vehicles, road infrastructure, networks, and pedestrians [2,18,23,33]. To this end, V2X service requirements [18] outline four types of applications to enable cooperative awareness for vehicles that provide smart services to their users: V2V applications expect vehicles located in proximity to each other to exchange information [19]; V2I enables vehicles to receive data broadcast from the smart transportation system, such as speed limits, weather conditions, and accident reports [3]; V2N applications use cellular networks to communicate with servers constituting the V2X management system [1]; and V2P applications exchange information between vehicles and pedestrians, *e.g.*, warnings to pedestrians but also vehicles about vulnerable road users [46]. With the recent focus on integrating AI into connected vehicles [50,53], the dimensions of V2X are only expected to become increasingly impactful. Inside the vehicle, data can be exchanged between the driver's personal devices and the in-vehicle infotainment and navigation system in the context of V2X [1,3,19,46]. Several frameworks have been proposed for the design of inside- and outside-the-vehicle interactions. For example, Detjen *et al.* [16] overviewed input modalities (eye gaze, mid-air gestures, speech) and output modalities (visual, auditory) for in-vehicle interaction; Bilius *et al.* [7] introduced a conceptual framework to operationalize proxemic interactions with smart vehicles; and Jansen *et al.* [25] proposed a design space for in-vehicle interactions in terms of individual input and output modalities, but without addressing user interface distribution.

2.3 Vehicle-to-Distributed User Interfaces

Bilius *et al.* [8] introduced V2DUIs by adapting generic design principles for DUIs [17,36,40,44,51] applicable to both inside- and outside-the-vehicle interactions [6,7,15,16,27]. The operational definition of V2DUIs refers to DUIs that integrate interactive systems from the ecosystem of a smart vehicle during the distribution of UI elements, I/O modalities, and tasks across drivers and passengers, their personal digital devices, and possible environments where interactions take place, including when outside the vehicle [7].

Based on an analysis of DUI frameworks [17,36,41,51] and V2X communications requirements for smart vehicles [18,23,33,54], Bilius *et al.* [8] proposed several guiding principles for V2DUIs, such as smart vehicle orientation, multi-device operation, multi-modal interaction, and multi-environment operation. For example, the smart vehicle orientation principle refers to the fact that smart vehicles already come equipped with many sensors, displays, and systems designed to interact with road infrastructure, other vehicles, and communication networks. Consequently, V2DUIs can address aspects of driving safety by enabling drivers to switch between I/O modalities as needed, without taking their hands off the wheel and eyes off the road. Besides user experience benefits provided by distribution of the interaction, impact is expected in driving safety through the implementation of V2DUIs. Unfortunately, this prior work remains purely conceptual and, to the best of our knowledge, has not been applied or evaluated empirically to date.

To address this gap, Section 3 presents an exploratory study designed to collect information about driver behavior with personal digital devices. In a first stage, we focus on how frequently and in what ways personal devices are used inside the vehicle. In a second stage, we collect drivers' perceptions of safety risks when using their personal devices while driving. We are also interested in how the interface can be distributed between in-vehicle systems and personal devices to minimize distraction and increase driving safety. Based on the collected information, we present in Section 4 an application of V2DUIs for a music player with an interface distributed across the in-vehicle infotainment system and the driver's smartwatch. The application integrates different I/O modalities, through touch gestures and output haptic feedback, integrated to reduce distraction while interacting with both the infotainment system and personal devices while driving.

3 Exploratory Study

To examine practical opportunities of V2DUI applications, we conducted an exploratory study to gain insights into drivers' needs and preferences regarding the use of their personal digital devices.

3.1 Participants

A total number of 24 drivers, of which 19 self-identified as male and 5 as female, aged between 19 and 60 years (M=32.5, SD=12.9), were recruited through convenience sampling to participate in our study. Their occupations and backgrounds were diverse, spanning engineers, laboratory technicians, professors, programmers, sales agent, students, and photographer. Three participants were unemployed at the time of the study. Participants' driving experience ranged from 1 to 26 years with daily driving time varying between 1 and 10 hours, and an average of 167,000 km traveled; see Figure 1 for demographic information about our sample.

3.2 Procedure and Measures

We implemented the study in the form of an online questionnaire addressing aspects of driver behavior and the use of personal devices while driving, such as frequency of use, types of interactions, perceived safety risks, and situational contexts for using digital devices. We grouped the questions into the following categories:

- *Demographic information.* Participants reported their age, gender, and professional occupation or field of education if not employed at the time of the study.
- *Driving experience and habits.* Participants provided details about their driving experience, including the number of years they had been driving, total mileage traveled, driving frequency, and driving purposes.
- *General use of digital devices.* We asked participants to indicate devices they were using regularly by choosing from a list—laptop, tablet, smartphone, smartwatch, and wireless headphones (multiple selections allowed)—and rate the frequency of use on a 7-point Likert scale with items ranging from 1 (never) to 7 (all the time).
- *Use of digital devices and the in-vehicle infotainment system while driving*. Participants were asked to report which functions they had been using on personal digital devices and the in-vehicle infotainment systems, the types of interactions, and the context in which they were most frequently using those functions while driving.
- *Measures of driver attention.* Participants provided information about their behavior when receiving calls while driving, the traffic context in which they were using their personal digital devices, any experiences involving accidents caused by device use, and perceptions of reaction times and safety concerns about the use of digital devices and the in-vehicle infotainment system while driving.
- We administered the *Distracted Driving Scale* [21] to evaluate phone-related distractions based on responses to eleven questions about phone usage, with scores ranging from 0 (low/none) to 44 (high); see Hill *et al.* [21] for details.

3.3 Results

Figure 1 provides an overview of the findings from our exploratory study conducted with drivers, which the following subsections present in detail, according to the questionnaire structure. For descriptive statistics, we report means (M) as a measure of central tendency and standard deviations (SD) as a measure of variation. Following infographic practices [14,28] used for creative data visualization [22], Figure 1 integrates all of the findings from our exploratory study to present them in context.

3.3.1 Driving experience and habits. Participants reported driving on average 2.4 hours per day (SD=2.0, Min=1, Max=10), covering an average of 167,000 km (SD=163, 000, Min=25, 000, Max=600, 000), with an averaged driving experience of 10.6 years (SD=8.4, Min=1, Max=26); see Figure 1.2 for this information in the context of all collected data in our exploratory study with drivers. Most of the participants (16/24=66.7%) reported driving daily, with 16.7% (4/24) nearly every day and 16.7% (4/24) at least once a week. Additionally, participants reported using their vehicles in a diversity of contexts, including commuting to work or school (19/24=79.2%), work-related tasks (7/24=29.2%), private travel (17/24=70.8%), visiting friends or family (21/24=87.5%), shopping (22/24=91.7%), excursions (18/24=75.0%), or for driving others (4/24=16.7%). These results reveal a diverse sample of participants in terms of driving needs and behavior, convenient for our exploratory investigation.

3.3.2 General use of digital devices. The highest frequency of device usage was observed for smartphones, with an average of 6.7 (SD=0.99) on the 1-7 scale. Laptop computers followed at 5.5 (SD=1.98), then wireless headphones at 3.8 (SD=2.1), smartwatches at 3.6 (SD=2.2), and tablets at M=3.1 (SD=2.0); see Figure 1.3. These results confirm the prevalence of smartphones in daily usage, and indicate a notable adoption level of wearable devices.

3.3.3 Use of digital devices and the in-vehicle infotainment system while driving. All participants reported using the in-vehicle infotainment system. Phone calls, operated through the integrated Bluetooth interface, were reported by 45.8% (11/24) of the participants, while 41.7% (10/24) mentioned using the GPS for navigation purposes; see Figure 1.4b. All participants indicated using smartphones while driving (Figure 1.4a), for which the most frequently used functions were listening to music and navigation assistance (16/24=66.7%), followed by hands-free calls (10/24=41.7%) and hand-held calls (8/24=33.3%), respectively; see Figure 1.4d. When asked about the purpose of using digital devices inside the vehicle, 62.5% (15/24) and 45.8% (11/24) of the participants reported using smartphones and smartwatches for purposes not related to driving, such as checking the time (10/24=41.7%), receiving messages (7/24=29.2%), making calls (7/24=29.2%), and reading notifications (6/24=25.0%); see Figure 1.4c. Regarding preferences for

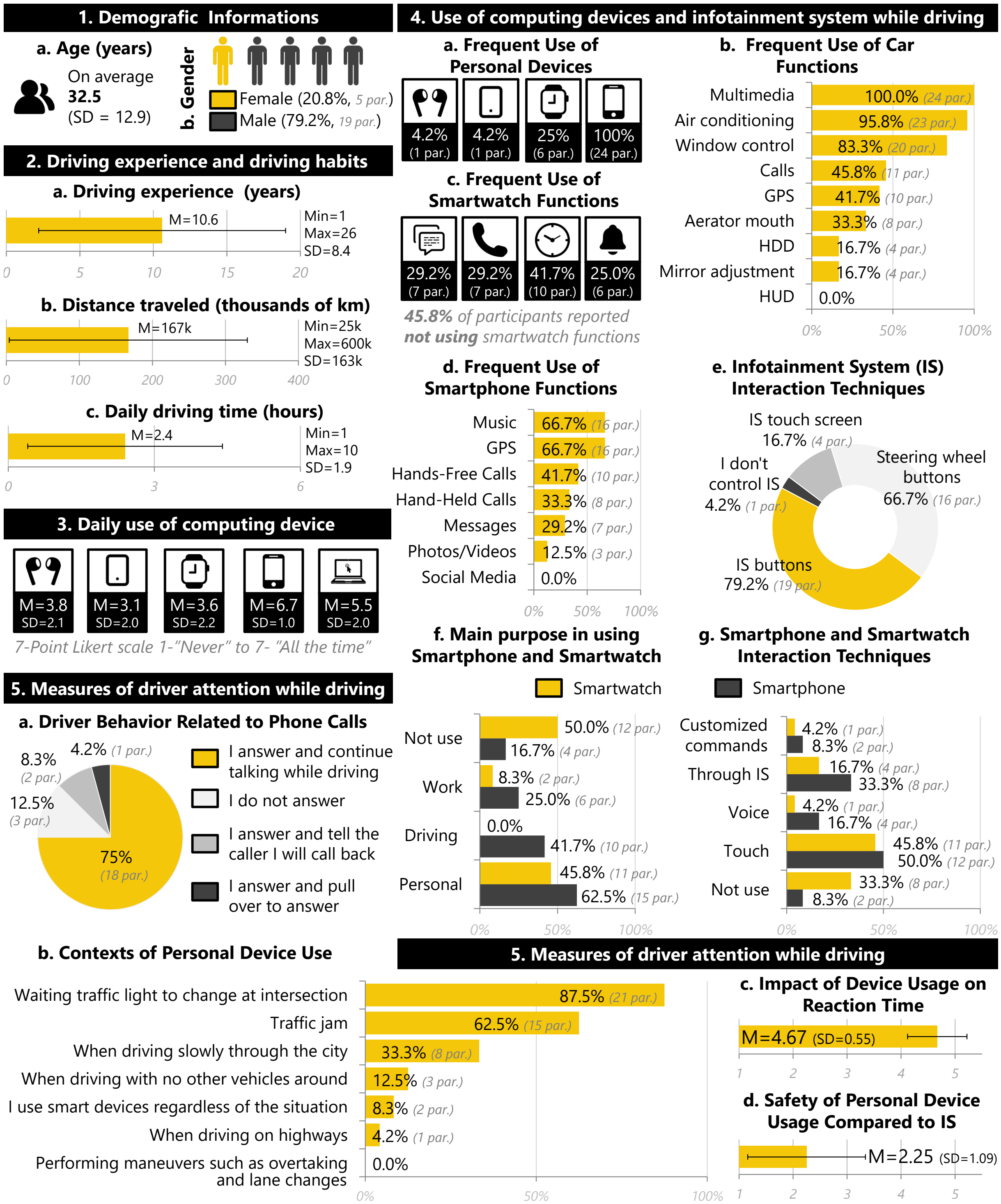

Figure 1: Demographic information, driving behavior, digital device use preferences inside the vehicle, and perception of driving attention and safety concerns collected from the twenty-four participants in our study. ***Notes:*** **we report means (M) as a measure of central tendency and standard deviations (SD) as a measure of variation.**

controlling the in-vehicle infotainment system, a significant majority (19/24=79.2%) reported using the integrated buttons, 66.7% (16/24) the steering wheel controls, while touch input was employed by just 16.7% (4/24) of the participants; see Figure 1.4e. However, touch input was the most frequently used modality in the case of personal digital devices, with 50.0% (12/24) of the smartphone users and 45.8% (11/24) of the smartwatch users employing them, with voice input following with a lower preference of 16.7% (4/24) and 4.2% (1/24), respectively; see Figure 1.4g for these results presented in the context of all collected data about driver experience, behavior, and preferences for digital device use inside the vehicle.

3.3.4 Driver attention and distracted driving. The Distracted Driving Scale [21] revealed an average score of 12.1 (SD=6.7, Min=0, Max=24), closer to the minimum than the maximum point of the [0, 44] range. A significant majority of the participants (21/24=87.5%) indicated that they had used personal devices while waiting for traffic lights to change and 62.5% (15/24) reported using them during short stops in traffic jams; see Figure 1.5b for more details. We found 75.0% (18/24) of the participants reporting they had answered calls and talked while driving (Figure 1.5a), and one (1/24=4.17%) was actually involved in a car accident as a consequence of using their digital devices while driving. In response to whether using devices in the vehicle affects reaction time, participants were in consensus with an average rating of 4.67 (SD=0.55) on a Likert scale ranging from 1 (totally disagree) to 5 (totally agree) but, when asked if they considered using a personal device to be safer than the in-vehicle system, they provided lower ratings, averaging 2.25 (SD=1.1); see Figures 1.5c and 1.5d for these findings presented in context.

3.4 Summary

Our exploratory study surfaced preferences, elicited from drivers of a diverse demographics, for using both the smartphone and the smartwatch inside the vehicle, with touch input use exceeding the frequency of voice commands, more frequently while at traffic lights or in slow traffic. This is despite a consensus that personal digital devices were perceived as strongly affecting reaction times and driving safety. Additionally, our results point to the combined use of the in-vehicle infotainment system and personal devices, with content consumption, represented by music, being the most frequently accessed function. Based on these findings, we present in the next section a V2DUI implementation for a music player application with an interface distributing interaction modalities across the in-vehicle infotainment system and the driver's smartwatch.

4 Demonstrative Application

To apply the V2DUI concept in a practical context and elicit preliminary user feedback, we developed a demonstrative application showcasing UI distribution for control and access to digital content with a use case informed by the findings of our study in Section 3.

4.1 Technical Implementation

We implemented a music player application[1] controlled with stroke-gesture input and providing vibrotactile feedback. Based on selection criteria for stroke-gesture recognizers [34], we adopted the $1 algorithm [52] to implement recognition of a gesture set for navigating playlists and controlling our application: *swipe left* and *swipe right* gestures to advance to the next or previous track, *swipe up* and *swipe down* to increase or decrease the audio volume, a *checkmark* to toggle between play and pause modes, drawing a *counterclockwise circle* to add a track to the favorites list and a *clockwise circle* to remove it, *letter "Z"* to play a favorite track, and the *zig-zag* symbol to play all tracks. We deployed the application on a tablet device, specifically a Samsung Galaxy Tab 4 with a 10-inch screen, 1280×800 resolution, and capability to detect up to ten simultaneous touches, installed on the car's front panel. Following each gesture, vibrotactile feedback was delivered to the user's wrist via a smartwatch, represented in our setup by a Galaxy Watch 3, to confirm successful gesture recognition. This setup was informed by our findings in Section 3 and supported by empirical results on touchscreen input assisted by on-wrist haptics for an enhanced user experience of synchronized touchscreen and wrist-based haptics [49]. Specifically, the confirmatory vibrations on the smartwatch implement the "addition" and "reinforcement" Wear+Touch techniques [49], previously introduced and evaluated in contexts other than in-vehicle interaction. The application was written in JavaScript and consisted of a client component running on the smartwatch, which exchanged JSON messages with the server component running on the tablet. For the vibrotactile feedback, we used VIREO [48] and VibViz [47], two online tools for the design and integration of vibrotactile patterns into applications. We implemented two short, exponentially increasing pulses for successfully completed actions, and two vibrations of constant amplitude but different duration for gesture recognition errors.

4.2 Evaluation

To gain preliminary insights into the usability of our V2DUI implementation, we conducted a study with five participants (four male and one female), which were recruited via convenience sampling. The study was conducted at the Ştefan cel Mare University of Suceava and adhered to the institution's ethical procedures. The task consisted of interacting with the music player application in an eyes-free condition, requiring the participants to keep their eyes on the road at all times. The participants sat in the driver's seat and, at random intervals when instructed by the experimenter, used the gestures enumerated earlier to perform specific commands in the music player application, such as advancing to the next track or adding a track to the favorite list; see Figure 2 for photographs captured during the study. For safety reasons, the car remained parked, but participants were instructed to keep their eyes on the road to simulate a driving scenario as closely as possible.

At the end of the study, participants completed a questionnaire to report their experience with the distributed interaction modalities in our V2DUI. The questionnaire included the System Usability Scale (SUS) [11], the Usability Metric for User Experience (UMUX) [20], and the Computer System Usability Questionnaire (CSUQ) [31], three established tools for assessing usability.

We found an average SUS score of 69 (SD=7.4), which can be interpreted as a grade "C" or "average" usability according to Lewis' [31] interpretation range, and as "good" according Brooke's [11] recommendations. This result was complemented by a UMUX score of

[1] Adapted from https://github.com/Davigl/vue-music-player.

Figure 2: Photographs captured during the usability study of the V2DUI, showing participants using touch input to control a music player application on the in-vehicle infotainment system with vibrotactile feedback delivered on the smartwatch.

73.3 (SD=13.4) and a CSUQ score of 2.5 (SD=1.0), both representing reasonably high evaluations [45], building confidence, albeit with the caveat of a small sample size in our preliminary evaluation, in the benefits of distributing interaction modalities by applying the V2DUI concept in a practical in-vehicle context. However, further research is needed to confirm these findings as well as to explore the broader implications for V2DUIs as well as opportunities for smart vehicles, some of which we explore in the next section.

5 Limitations and Future Work Opportunities

Our two studies present limitations in sample size—twenty-four drivers in the first study and five participants in the usability study—but they represent the first practical application of the V2DUI concept [8] to gain initial insights into drivers' preferences and usability aspects of distributing interface elements and interaction modalities across devices within the in-vehicle environment. Future empirical investigations with larger sample sizes are recommended to validate and consolidate our findings. These investigations could consider other devices, such as the smartphone, and specific interaction contexts for in-depth analysis; for example, using the smartphone while effectively picking it up *vs.* controlling apps from the smartphone through the infotainment system via a Bluetooth connection. While both contexts of use involve touch input, the associated physical and cognitive demands on the user present important differences. Regarding other modalities, such as speech, these differences are likely to be smaller in extent, although further work is recommended to understand the impact of direct, via the smartphone, and indirect, via the infotainment system, use of apps for input modalities other than touch and gesture. The moments when touch input is used, *e.g.*, during actual driving *vs.* when stopped at a traffic light or in traffic (Figure 1), also impose distinct cognitive and physical demands, to be investigated through the lens of drivers' behavior and preferences involving V2DUIs.

Exploring multimodal interaction in the light of the benefits brought by V2DUIs to adapt user interfaces dynamically based on how and when drivers engage with them has the potential to reduce distractions while behind the wheel, an aspect to be examined more closely in future work. Also, new V2DUI scenarios could be explored, involving other personal digital devices, such as fitness bands [29], digital jewelry [24], or advanced health monitoring wearable systems [39], as these technologies gain wider adoption among consumers. Even with different devices, the underlying distribution principle would remain unchanged: the V2DUI distributes interaction modalities to enable effective input while delivering suitable feedback to the driver to minimize distraction during driving and integrating the driver's personal devices—two insights emerging from our study in Section 3. To further address critical challenges of interaction while driving, computational models [32] could be integrated into the V2DUI conceptual framework [8].

Another promising direction is represented by consolidating applications of V2DUIs with a design space [9,10] encompassing relevant dimensions, such as devices and sensors [25], spatial relationships [4], and distribution functions [36]. A design space typically includes a characterization range (potential dimensions and design points), an acceptable range (admissible parameter combinations), and an operating range (experimentally validated combinations) [43], while pursuing three virtues [5]: *descriptive*, by systematically categorizing approaches using consistent terminology; *comparative*, by enabling parameter-based comparisons between approaches; and *generative*, by identifying gaps for further exploration and inspiring new ideas. Building on these virtues, a V2DUI design space could leverage Design Space Exploration [42], a systematic method for exploring potential dimensions based on parameters of interest. These future developments will strengthen the theoretical foundation of V2DUIs and enable further empirical examination and application development for various contexts of use in terms of devices (in-vehicle, mobile, and wearable), users (drives and passengers), and application types (from content consumption inside the vehicle to controlling the smart vehicle). Furthermore, understanding how the distribution of interface elements and interaction modalities can positively impact driving safety is especially important for the integration of V2DUIs in smart vehicles.

6 Conclusion

We explored drivers' preferences for digital device use inside the vehicle and conducted a usability study to evaluate a preliminary implementation of a V2DUI designed to distribute interaction modalities across the in-vehicle infotainment system and the driver's smartwatch. Our findings revealed concerns about distracted driving, which our V2DUI implementation sought to address with eyes-free interaction and promising usability scores. Moreover, our empirical explorations revealed the need for a design space to guide systematic development of practical V2DUIs. This would require further formalization, such as incorporation of distribution primitives [35] and cross-device interaction styles [12], two foundational approaches in the development of DUIs in other domains, to enable more structured design and development of V2DUIs. We believe that V2DUIs hold potential for increasing driver performance and enriching the overall experience of in-vehicle interactions and traveling, and we recommend more investigations in this area.

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