Smart Vehicle Proxemics: A Conceptual Framework Operationalizing Proxemics in the Context of Outside-the-vehicle Interactions

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Abstract. We introduce *smart vehicle proxemics*, a conceptual framework for interactive vehicular applications that operationalizes proxemics to *outside-the-vehicle interactions.* We identify four zones around the vehicle affording different kinds of interactions and discuss the corresponding conceptual space along three dimensions (physical distance, interaction paradigm, and goal). We study the dimensions of this framework and synthesize our findings regarding drivers' preferences for (i) information to obtain from their vehicles at a distance, (ii) system functions of their vehicles to control remotely, and (iii) devices (e.g., smartphones, smartglasses, smart key fobs) for interactions outside the vehicle. We discuss the positioning of smart vehicle proxemics in the context of proxemic interactions more generally, and expand on the dichotomy and complementarity of outside-the-vehicle and inside-the-vehicle interactions for new applications enabled by smart vehicle proxemics.

Keywords: Smart vehicles · Connected vehicles · Proxemic interactions · Conceptual space · Outside-the-vehicle interactions · Study.

1 Introduction

Connected vehicles [20] can access online resources and services, integrate with the cloud and the Internet-of-Things [29], communicate with other connected vehicles and the road infrastructure [6], and interact with drivers' and passengers' personal smart devices [46,55] to enable safer and more comfortable car journeys and increased road safety [18]. Smart cars with embedded AI [30] further enrich the car traveling experience. In this context, interactions between drivers and their smart, connected vehicles need keeping pace with the advances in vehicular technology [18, 20] towards a rich and rewarding user experience of driving.

The HCI community has proposed a variety of interactive techniques, modalities, and devices to mediate inside-the-vehicle interactions — including voice input, mid-air gestures, haptic feedback, and others; see [8] for an overview. However, while much of the focus has been devoted to in-vehicle input [3, 4, 9, 11, 21, 41, 52], *the space outside the vehicle has been largely overlooked in terms of the*

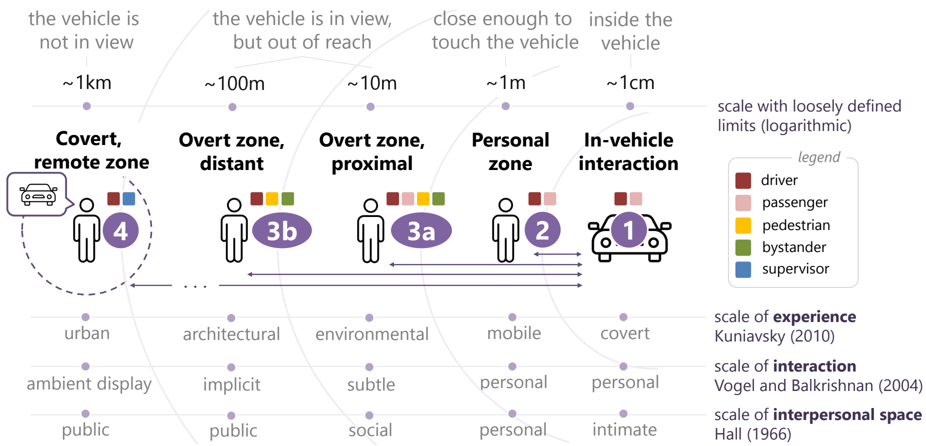

Fig. 1. An illustration of the smart vehicle proxemics framework with four distinct zones: ❶ inside the vehicle, ❷ personal interaction, ❸ overt interaction (proximal and distant), and ❹ interactions from the covert zone. While zones ❶ and ❹ have been studied before in the HCI and the intelligent transportation communities, interactions outside the vehicle corresponding to zones ❷ and ❸ have been mostly overlooked.

opportunities it can bring for new interactive vehicular applications. The most common interactions currently available to drivers when outside their vehicles are locking and unlocking the car and opening the trunk. Examples from the automotive industry include the Tesla key ring[3] and bracelet[4] leveraging NFC/RFID for remote access; the BMW Display Key,[5] with an integrated display, enables access to information about the vehicle from a distance; and smartphone apps[6] are available to assist with locating the car in a crowded parking lot. Recent work [24] has proposed integrating smart rings with smart vehicles for both inside and outside-the-vehicle interactions, e.g., the ring replaces steering wheel controls when inside the vehicle and, via a gesture, opens the trunk when outside, but such explorations are still at an incipient, mostly conceptual level.

In this context, there is an enticing practical opportunity for exploring complementing interactions with smart vehicles with a new design space dedicated to *outside-the-vehicle* interactions. To mitigate this kind of exploration, our work contributes a systematic categorization of the relevant design dimensions in the context of outside-the-vehicle interactions. We do this by leveraging notions of Edward Hall's Proxemics theory [28], which studies the nuances of people's interactions at different levels of proximity, and correlates people's *physical* distance to *social* distance. Hall effectively categorized person-to-person interactions in structured zones — intimate, personal, social, and public — and his work has inspired the application in many other contexts. In particular, *proxemic inter-*

[3] https://www.teslaring.com
[4] https://www.teslawearable.com
[5] https://www.bimmer-tech.net/blog/item/118-bmw-display-key
[6] https://play.google.com/store/apps/details?id=com.elibera.android.findmycar

actions [7, 26] identified key dimensions (distance, orientation, motion, identity, and space) most relevant for the design of proxemic-aware people-to-device interactions. This has been applied in many contexts, such as for large surfaces [5,54], ambient displays [58, 59], and television [57]. Similar to how proxemics has been applied to ubicomp [26], our work operationalizes proxemics for smart vehicles, facilitating a more systematic exploration of interactive applications that exploit the space around the vehicle. In particular, we introduce a formalization of the interactive zones around the smart vehicle and a conceptual space for outside-the-vehicle interactions in the form of the *smart vehicle proxemics framework.*

In summary, our key contributions are:

1. We operationalize proxemics [28] for outside-the-vehicle interactions in the *smart vehicle proxemics framework*, and propose a four-zone proximity space for vehicles informed by proxemic interactions [7,26]; see summary in Fig. 1.
2. As part of this framework, we formalize outside-the-vehicle interactions by introducing a conceptual space with three key dimensions: (1) the *distance* between the driver and their vehicle, (2) the *paradigm* to interact with the vehicle, and (3) the driver's *goal* that guides the interaction process.
3. We report results from a study with drivers to further explore these dimensions of the framework, in which we elicited 65 drivers about the type of information they would like to obtain and the system functions they would like to control for their vehicles from a distance, and we draw implications for outside-the-vehicle interactions in the context of smart vehicle proxemics.

2 Related Work

Much of the related work in automotive user interfaces (AutoUIs) has primarily focused on interactions designed for inside the vehicle [3, 4, 9, 11, 21, 41, 52]. Also, prior work from intelligent transportation systems has examined communications between pedestrians and vehicles in the context of autonomous driving cars and increasing road safety [22, 23, 36]. In this section, we synthesize this prior work, but also the relevant literature on proxemic interactions [7, 26, 27, 34, 63] that identified proximity zones around interactive systems, and which we apply in our context. But first, we discuss the concept of a smart vehicle and its recent modeling [49, 50] as a specific kind of a smart environment.

2.1 Smart, Connected Vehicles

A connected vehicle engages in communications with other vehicles, the road infrastructure, services from the cloud, and drivers' and passengers' smart devices to collect and generate data that improves its performance [20]. Services provided by connected vehicles include detection of driver fatigue and stress [20,43], accident prevention [20, 38, 43, 56, 64], interaction with smart driving assistants [16, 20, 38, 43, 56, 64], parking assistance [20, 43, 56], traffic monitoring [20, 43, 56], integration with social networks [20,43], and media streaming inside the vehicle, including high-definition video and Augmented Reality (AR) content [50]. For example, Chirca *et al.* [17] introduced a valet parking system for fully autonomous vehicles; Liang *et al.* [36] examined a vehicular application scenario where traffic participants shared information about their speed, locations, and time of arrival to reduce delays in traffic; Wang *et al.* [60] addressed aspects of the security of the data collected by connected cars when integrated with cloud computing; and Aiordăchioae *et al.* [1] discussed vehicular lifelogging, where passengers document their car journeys with lifelogging technology, such as smartglasses.

Particularly relevant for our scope is Schipor and Vatavu's [49,50] modeling of the smart car as a specific kind of a smart environment [19]. Their work describes the goal of reusing available software architectures specifically designed for smart environments [51] in the context of smart cars, such as for the delivery of video and AR inside the vehicle [50]. Beyond this original goal, we argue that modeling the smart car as a specific kind of a smart environment allows reusing the design principles of ambient intelligence systems [47] and ambient media [44] for new interactive vehicular applications that connect to online services and resources.

2.2 Interactions Inside the Vehicle

Techniques based on car controls, touchscreens, mid-air gestures, voice, and multimodal input have been proposed for in-vehicle interactions towards increased road safety and a better user experience for drivers and passengers [3, 4, 41, 52]; see Bilius and Vatavu [8] for a synopsis of input modalities for in-vehicle infotainment. For example, prior work has examined touch input on the steering wheel [3, 4] and gestures in mid-air [11, 37, 41] so that drivers could keep their eyes on the road while interacting with their cars. Furthermore, voice input inside the vehicle has been addressed in terms of design guidelines [31, 55] and technical aspects of speech recognition [2, 53]. Bilius and Vatavu [9] reported a comparative analysis about drivers' and passengers' preferences for gesture and voice input inside the vehicle by employing questionnaires and the end-user elicitation method [61]. Multimodal input techniques that combine buttons and car controls, touch, gesture, and voice input offer increased flexibility that proves useful in many situations during driving [21, 24]. Also, wearable devices have been recently considered for in-vehicle input, such as the opportunity of smart rings to complement and even replace the controls on the steering wheel [24].

2.3 Interacting with the Vehicle from a Distance

A large body of work exists on the communication between vehicles and pedestrians in the context of intelligent transportation systems to increase road safety. For example, Domeyer *et al.* [23] focused on vehicular cues to signal pedestrians when they can safely cross the street. Lee *et al.* [35] examined interactions in mixed traffic environments for cross-walking priority. Markkula *et al.* [39] proposed a taxonomy for the behavior of traffic participants including hand gestures, making eye contact, slowing down, using vehicle lights and body movements to express pedestrians' intentions to cross the street and drivers' intentions to give them priority, respectively. Dey and Terken [22] examined the importance of gestures and eye contact for the communication between pedestrians and drivers.

Remote control of the vehicle has been implemented by several car manufacturers. For instance, smart parking of the Volkswagen Touareg can be done from a smartphone app[7] and BMW cars enable drivers to connect to the in-vehicle infotainment system from the smartphone or the Display Key[8]. The Tesla key fob[9] summons the vehicle, the Tesla ring[3] and bracelet[4] lock/unlock the car, and a smartphone app[10] controls the air conditioning, lights, and engine. Although these devices are useful to remotely control the vehicle, their functionality seems to be only the beginning of the wider design space of out-of-vehicle interactions.

2.4 Proxemic Interactions

Edward Hall's Proxemics theory [28] studies people's implicit use of interpersonal space when interacting with others. Most importantly, Hall correlates personal distance to social distance, and structured people's interpersonal space into four explicit zones: the *intimate* zone up to 0.5m, *personal* between 0.5m and 1m, *social* up to 4m, and the *public* zone beyond 4m. Beyond functioning as an analytical lens into people's implicit use of space, Proxemic theory has inspired work in ubiquitous computing environments to mediate people's interactions with technology. Proxemic interactions [26] draw inspiration from Hall's theory, and designed interactive systems that could sense the relative distance and orientation of users, and adapt and react accordingly to this information. For example, focusing on media spaces, Greenberg and Kuzuoka [25] designed digital and physical surrogates to mediate interactions between people. Addressing interactions with public ambient displays, Vogel and Balakrishnan [59] discussed how orientation and proximity to the display are indicators for the engagement with the display. Tănase *et al.* [54] designed an interactive tabletop system that detected and tracked users in its proximity by leveraging short-range distance sensors. By exploiting the proximity information, content was adapting to the location of the user, e.g., a PDF document could automatically rotate to be read correctly by the user moving around the tabletop. Later, Annett *et al.* [5] introduced a proximity-aware multi-touch tabletop with higher sensing resolution.

Considering the fine-grained nuances of proxemic theory and operationalizing it for person-to-device interactions have inspired the design of new types of interactions based on the distance, orientation, movement, identity, and location of entities in a smart environment [7, 26, 40]. For example, Mumm and Mutlu [42] studied proximity between humans and robots; Ledo *et al.* [34] proposed proxemic-aware controls for interactions employing a handheld device and surrounding appliances; proxemic interaction with museum exhibits was implemented by Wolf *et al.* [62] by leveraging video projections on the floor; Yeh *et al.* [63] studied proximity interactions for drones; and Grønbæk *et al.* [27] proposed cross-device techniques based on proximity to foster social interaction.

[7] https://play.google.com/store/apps/details?id=de.volkswagen.pap
[8] https://www.bimmer-tech.net/blog/item/118-bmw-display-key
[9] https://shop.tesla.com/search?searchTerm=KEYS
[10] https://www.tesla.com/support/tesla-app

2.5 Summary

A considerable amount of work has been devoted to make in-vehicle input more efficient for drivers, while communication between vehicles and pedestrians has been examined in intelligent transportation systems to increase road safety. In this context of sustained innovations in smart vehicular technology, we are lacking a more systematic exploration of the opportunities offered by the interactive space *around* the vehicle, which prevents designs of new automotive UIs where drivers can interact with their vehicles not only from a distance, but adaptively according to the distance to their vehicles. Next, we formalize this space in the form of a smart vehicle proxemics framework for outside-the-vehicle interactions, and leverage proxemics theory to more systematically structure this space.

3 Smart Vehicle Proxemics Framework

We introduce the smart vehicle proxemics framework (Figure 1) to structure the physical space around a smart vehicle in analogy with Hall's [28] zones of personal space and by drawing from the literature on proxemic interactions [7, 26, 40]. By applying proxemics as a lens to structure this space, we identified the following four distinct zones for smart vehicle proxemics:

❶ **In-vehicle interaction zone.** The driver is inside the vehicle and operates the car controls, touchscreens and the infotainment system, the steering wheel controls, etc. As discussed in Section 2, this interactive zone has been a particular research focus in the AutoUI community (e.g., [3,4,9,11,21,41,52]).

❷ **Personal interaction zone.** The driver is outside the vehicle, but close to the vehicle so that they could comfortably reach and touch it. We approximate the personal zone of about 1m, roughly an arm's length.

❸ **Overt interaction zone.** The driver is outside the vehicle, but too far away to reach and touch the vehicle. This zone is characterized by the driver having a clear view of their car from a physical distance roughly between 1m and 100m, but these thresholds are by no means fixed ones. What is important is that a clear view of the vehicle is possible, which makes this zone "overt." In the overt zone, we distinguish between two subzones: *proximal interaction* near the vehicle, such as at less than 10m away, and *distant interaction*, e.g., between 10m and 100m; see Figure 1. In the proximal zone, the driver is very close to their vehicle: they have just exited the vehicle or are approaching it. In this zone, short-range communication devices start operating, such as Class-2 and Class-3 Bluetooth devices,[11] and voice input becomes feasible to be picked up by sensors from the vehicle. In the distant zone, the driver is farther away, yet the vehicle is still in their field of view. In this zone, long-range Class-1 Bluetooth devices operate,[12] hand signaling can be picked

[11] Class-2 Bluetooth operates at a typical range of 10m; Class-3 at about 1m; see more details on the Bluetooth SIG page https://www.bluetooth.com/learn-about-bluetooth/key-attributes/range.

[12] Class-1 Bluetooth operates at a typical range of 100m; see the link above.

up by high-resolution video cameras from the car, and smartphone apps can connect to the car via the Internet. Thus, distinct input modalities are available to drivers when either *proximal* or *distant* in the overt zone.

❹ **Covert interaction zone**. The driver is outside the vehicle but, unlike in the previous zones, the vehicle is covert from view. This zone covers large distances, where the driver is remote, e.g., at home. We use the threshold of 100m as an approximation of this zone, but depending on the context the actual value of this distance is likely to vary. From this distance, Internet-based communication with the car is the norm, and different goals for interacting with the vehicle are expected compared to the previous zones, e.g., Is my car safe? Has my parking ticket expired? Where did I park? [29].

It is important to note that the physical limits of 1m, 10m, and 100m are just an approximation of the thresholds to physically separate these four interaction zones around the vehicle and, similar to the work in proxemics and proxemic interactions [7, 26, 28], they are not static or fixed boundaries. The spatial thresholds of these zones are informed by spatial and technical constraints. For example, in the personal zone 1m represents an arm's reach, and the visual acuity in the overt zone decreases with distance, e.g., between 10m and 100m. The overt zone distance thresholds also correlate to the operating ranges of Class 1, 2, and 3 Bluetooth devices, which is a technology commonly used in smartphones, smartwatches, bracelets, rings, etc. to interact with the vehicle. Moreover, these thresholds form a geometric progression with the common ratio 10 that connects directly to Kuniavsky's [33] *scales of experience* for ubicomp environments, from mobile (1m) to environmental (10m), architectural (100m), and the urban scale (1km). Figure 1 also shows correspondences between these zones and Vogel and Balakrishnan's [59] *scales of interaction*: our in-vehicle ❶ and personal ❷ zones, where the driver can reach and touch the car, are in direct correspondence with the personal interaction zone of an ambient display; our overt zone ❸, with its proximal and distant delineations, corresponds to Vogel and Balakrishnan's subtle and implicit interaction zones, respectively; while when the driver is in the covert zone ❹, the vehicle can be seen as situated in the city landscape ambient.

Given that interactions in zones ❷ and ❸ have not been well-explored in the scientific literature, we introduce a conceptual space to inform interaction design with the smart vehicle across these zones. Our conceptual space has three dimensions corresponding to the *interaction paradigm* chosen by or available to the driver depending on the physical *distance* from their vehicle and the driver's *goal* for initiating interaction with their vehicle (see Figure 2):

1. **Distance.** These are the four spatial zones of our framework introduced above: in-vehicle, personal, overt (proximal and distant), and covert. The physical distance to the vehicle constrains the driver's options for possible interactions and devices, e.g., some Bluetooth devices operate within a limited range, such as 10m, while others up to 100m.
2. The **interaction paradigm** dimension includes the input modality, technique, and device employed to implement the interaction with the vehicle. Options range from touching the vehicle (i.e., when close to the car in the

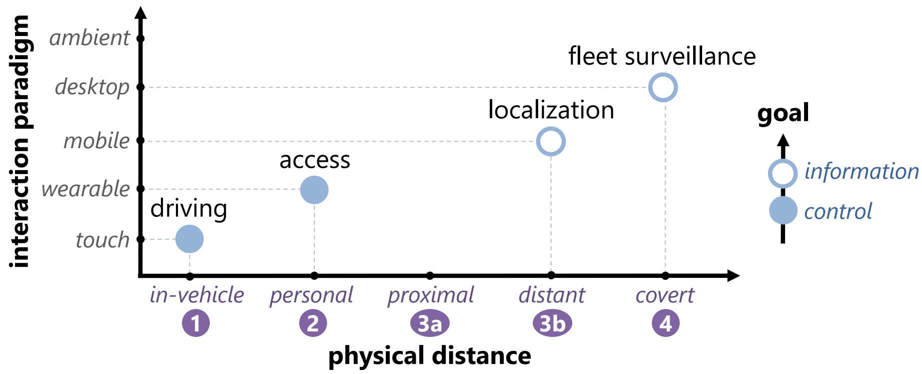

Fig. 2. Conceptual space for outside-the-vehicle interactions with three dimensions: distance to the vehicle, interaction paradigm, and the driver's goal. *Note:* several applications, e.g., fleet surveillance, car localization, etc., are highlighted in this space.

personal zone ❷) to using a Bluetooth mobile/wearable device (when near the car in the overt zone ❸) to using a desktop PC (e.g., to locate the car, open a live video stream from the car, etc.), or an ambient device when in zone ❹ (e.g., the Ambient Orb[13] could be used to gently inform — at the periphery of the user's attention — that the car insurance is about to expire).

3. **Goal of the interaction.** The goal impacts the type of interaction between drivers and vehicles, e.g., checking if the car is locked when near the vehicle ❸ *vs.* checking if the car is safe when not in direct view ❹.

Figure 2 illustrates our conceptual space and exemplifies various applications for outside-the-vehicle interaction. For example, fleet surveillance [48] is located at the intersection of the covert zone ❹, desktop PCs, and information seeking goals; access to the vehicle [13] is located at the intersection of the personal zone ❷, a mobile device, and seeking control; and localization of the vehicle [29] at the intersection of the overt distant zone ❸ with mobile applications with the goal of obtaining information about or from the vehicle. To validate the usefulness of these dimensions of the framework, in the next section we examine drivers' preferences for interactions to be performed outside the vehicle.

4 User Study: Understanding Drivers' Outside-of-vehicle Interactions across the Framework Dimensions

We conducted an exploratory study to understand drivers' needs and preferences for interacting with their vehicles from a distance, with a particular focus on interactions across the dimensions of the framework. We implemented the study using an online questionnaire and addressing proximity zones ❷, ❸, and ❹ from Figure 1 and the dimensions from our conceptual space from Figure 2.

[13] https://ambientdevices.myshopify.com/products/stock-orb

4.1 Participants

A total number of 65 drivers (46 male, 19 female), 19 to 54 years old (M=31.0, SD=10.5 years), participated in our study. We recruited participants via mailing lists, social networks, and from the student and staff body of our university. With one exception,[14] all of the participants had at least one year of driving experience. Participants' occupations and backgrounds were diverse including, in alphabetical order: administrator, cashier, construction worker, engineer, professional driver, economist, medical assistant, microbiologist, military personnel, professor, scientific researcher, sales consultant, software engineer, student, warehouse operative, and one participant was unemployed at the time of the study.

4.2 Task

Questions were grouped into the following four categories:

1. **Demographic information.** Participants filled out their age, gender, and professional occupation (or, in the case they were not employed at the time of their participation in the study, their field of education).
2. **Driving experience and driving habits.** Participants were asked to enter information about their driving experience, such as the number of years since they were driving, total mileage traveled in km, how frequently they were driving and for what purpose, and with whom they were regularly traveling.
3. **Use of computing devices.** We asked participants to indicate devices they were using on a regular basis by choosing from the following list (multiple selections were allowed): laptop computer, tablet, smartphone, smartwatch, smartglasses, smart ring, smart bracelet, wireless headphones, neural headset for brain-computer interfaces, and other. These categories of devices were informed by the scientific literature on in-vehicle input, but also by their prevalence (e.g., smartphones), emergence (e.g., smartwatches [55] and smartglasses [15]), and opportunities for the future of automotive driving assistance systems (e.g., neural headsets [14]).
4. **Preferences for outside-the-vehicle interactions.** Participants were asked to list the types of information they would like to obtain about or from their vehicles from various interaction zones (Figure 1). Since in-vehicle interactions corresponding to zone ❶ have been studied in-depth in the literature, our questions focused on zones ❷, ❸, and ❹. Also, for each of these zones, we elicited participants about preferences for vehicle functions they would like to control from a distance. Finally, we asked participants about which devices they believed would be best suited to perform those interactions and rate the suitability of those devices using 5-point Likert scales with values ranging from 1 (not suitable at all) to 5 (very suitable).

4.3 Design

Our study was a 1×3 within-subjects design with the following variables:

[14] One participant had a driving experience of six months only.

1. PROXIMITY-ZONE, independent nominal variable with three conditions representing zones ❷, ❸, and ❹ (see Figure 1). This variable corresponds to the *distance* dimension in our conceptual space illustrated in Figure 2.
2. VEHICLE-FUNCTION, dependent variable with values collected as open-ended feedback representing functions that participants would like to control from outside the vehicle. Functions are located along the *goals* axis in our conceptual space from Figure 2.
3. TYPE-OF-INFORMATION, dependent variable, with values collected as open-ended feedback representing information to obtain about the vehicle from outside the vehicle. Type of information is also located along the *goals* axis.
4. DEVICE, dependent nominal variable with the following conditions: (1) smartphone, (2) smartwatch, (3) smartglasses, (4) smart ring, (5) smart bracelet, (6) neural headset, (7) smart car keys, (8) smart clothes, (9) tablet, and (10) PC. These conditions represent various types of interactive devices that could be used to implement outside-the-vehicle interactions and correspond to the *interaction paradigm* dimension in our conceptual space from Figure 2. Categories (1) to (8) apply for all the proximity zones, while categories (9) and (10) were available only for the questions referring to the covert zone ❹.

5 Results

We present results about the types of information that our drivers reported they would like to obtain about their vehicles or from their vehicles from a distance as well as preferences for vehicle functions to control from a distance. But first, we briefly present a characterization of our sample of participants to appreciate the generalizability of the results from our exploratory study.

5.1 Characterization of the Sample of Participants

The driving experience of our participants ranged between 6 months and 32 years with a mean of 7.6 years (SD=6.6); see Figure 3, left. Participants reported having traveled between 200 km and 2,000,000 km[15] with an average of 125.8 (SD=289.3) thousands kilometers; see Figure 3, right. Almost half of the participants (44.6%) reported driving everyday, a quarter (26.2%) almost daily, 13.8% once a week, and 15.4% only occasionally (less than once a week). The majority of our participants (73.8%) reported driving alone, but also with their families (69.2%) and friends (43.1%), and some (18.5%) with coworkers. The cars were used for various activities, such as for work (29.2%), commuting (72.3%), driving others (26.2%), making private trips (67.7%), shopping (84.6%), visiting family (80.0%), and for holiday travels (67.7%), respectively.

Figure 4 shows devices used on a regular basis by the drivers from our sample. All drivers reported smartphones (100%), nearly all reported laptop computers (93.8%), and about half used wireless headphones (47.7%) and tablets (44.6%)

[15] A professional driver.

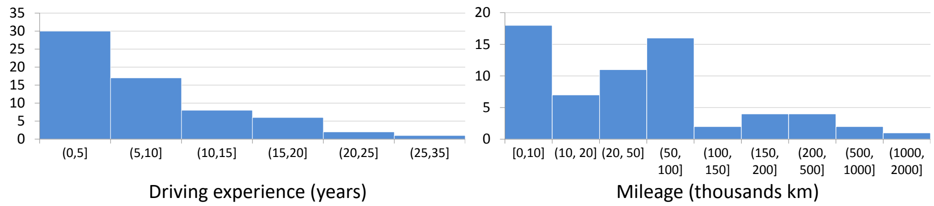

Fig. 3. Driving experience (left) and mileage (right) for our sample of drivers.

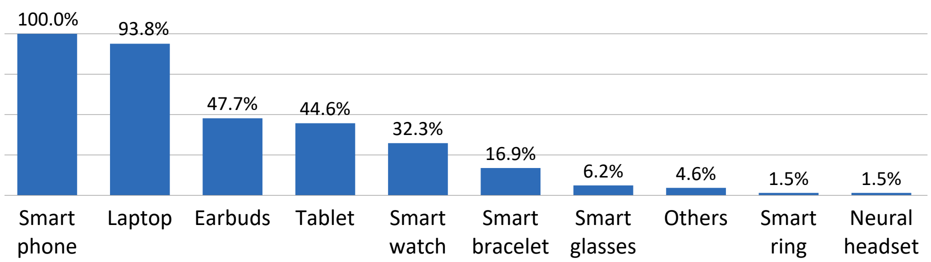

Fig. 4. Computing and personal devices used by our participants on a regular basis.

on a regular basis. One in three participants (32.3%) reported smartwatches, and one in six (16.9%) smart bracelets. Four participants had occasionally used smartglasses and one reported having used a smart ring and a neural headset.

This data reveals a diverse sample of participants with diverse driving experience and behavior and employing the vehicle for a variety of goals and needs, reflective of the diverse behavior of the driver population; see Kim and Tefft [32] for data from the AAA Foundation for Traffic Safety American Driving Survey. The results about devices used by our participants show the prevalence of smartphones, but also the emergence of new devices, such as smartwatches and bracelets, as representative upcoming categories of ubiquitous personal devices. The diversity observed in our sample is beneficial for the purpose of our exploratory study, enabling us to gain insights from a diversity of opinions.

5.2 Preferences for Information to Receive from the Vehicle at Different Proximity Zones

We collected a total number of 579 responses from our participants regarding the types of information they would like to obtain about or from their vehicles when in the proximity zones ❷, ❸, and ❹ (8.91 responses on average per participant and 2.96 responses on average per participant and proximity zone). Thematic grouping [12] of the responses revealed the following categories:

I_1. **Identification:** Information regarding vehicle identification, such as manufacturer and make, expiry date on the vehicle insurance, service schedule, vignette, the expiry date/time on the parking ticket, etc.

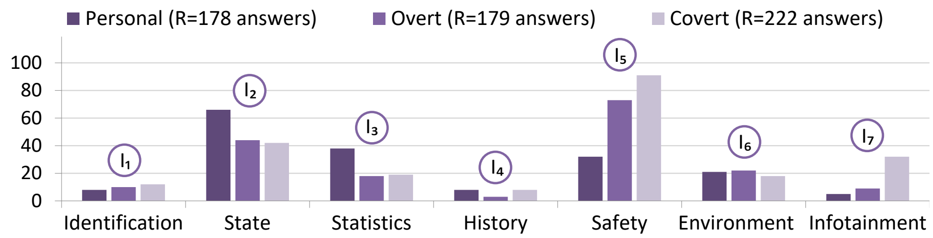

Fig. 5. Preferences for types of information to obtain from or about the vehicle from a distance. See the text for a description of information categories I_1 to I_7.

I_2. **State:** Information regarding the vehicle's technical state and inspection, its history of failures, the functional state of the on-board sensors and systems, tire pressure, engine temperature, battery level, etc.

I_3. **Statistics:** Information regarding consumption statistics, such as the car's fuel level, windshield fluid left available.

I_4. **History:** Information regarding the travel history of the vehicle, e.g., recent travels, last trip, total mileage, average speed.

I_5. **Safety:** Information regarding vehicle safety and security with respect to factors external to the vehicle, e.g., weather, break-in attempts, hand brake, the car being parked correctly, checking if the car is properly locked, etc.

I_6. **Environment:** Information about the in-vehicle environment, such as the inside temperature or the presence of personal objects, such as phone or wallet, that might have been forgotten inside the vehicle.

I_7. **Infotainment:** Information about the in-vehicle infotainment system, such as radio settings, music playlists, to do lists compiled and saved in the car.

Figure 5 shows the frequency of each thematic category I_1 to I_7 for each proximity zone, revealing several trends. For example, participants were more interested about the security and safety of their vehicles when in the covert zone ❹ (91 suggestions about safety), from where a direct view to their vehicle was not possible, rather than from the personal zone ❷ (32 preferences). Also, participants were more interested in obtaining technical information about their vehicles when near the vehicle in zone ❷ (66 suggestions) than when farther away (44 and 42 suggestions, respectively, for zones ❸ and ❹).

5.3 Preferences for Vehicle Functions to Control at Different Proximity Zones

We received 554 responses from our participants regarding vehicle functions they would like to control from a distance (8.52 responses on average per participant and 2.84 on average per participant and proximity zone). Similar to before, we applied thematic grouping [12] and identified the following categories:

F_1. **Infotainment:** Control of the in-vehicle infotainment system, such as the audio, GPS, list of contacts, connecting to and screen sharing of the in-vehicle infotainment system, access to the video cameras installed in the vehicle.

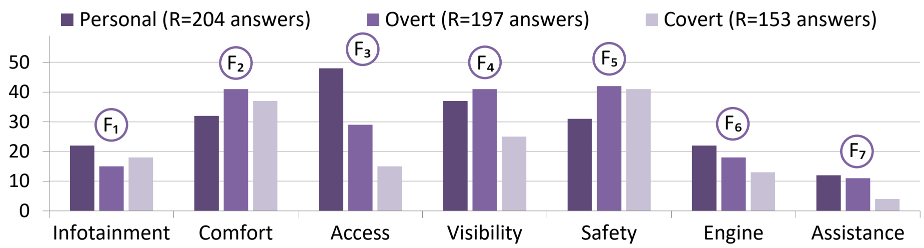

Fig. 6. Preferences for types of vehicle functions to control from a distance. See the text for a description of function categories F_1 to F_7.

F_2. **Comfort:** Control of functions for the comfort of passengers, such as seats heating, air conditioning, and the inside temperature.

F_3. **Access:** Access to the vehicle, e.g., opening the trunk, doors, windows.

F_4. **Visibility:** Visibility-related functions includes turning on/off headlights, hazard lights, wiping windows.

F_5. **Safety:** Control of functions about the safety and security of the vehicle, such as locking/unlocking the vehicle, setting the alarm, pulling the handbrake.

F_6. **Engine:** Engine control.

F_7. **Assistance:** Control of functions related to the driving assistance system, such as the parking assistant, summoning the car, driving assistance mode.

Figure 6 shows the frequency of each category for each proximity zone ❷, ❸, and ❹. Participants were more interested in controlling the vehicle security and safety systems when in the proximal zone ❸ (42 suggestions) rather than from the personal ❷ (31) or covert ❹ zones (41). They were also interested in access to the vehicle in zone ❷ (48 suggestions).

5.4 Preferences for Devices for Outside-the-Vehicle Interactions

Figure 7 shows participants' ratings of devices for outside-the-vehicle interactions. Results showed that the smartphone received the highest rating (M=4.62 on a scale of 5), followed by the smart key (M=4.12), smartwatch (M=3.95), and smart bracelet (M=3.40). The other devices from our list (see Section 4.3) received preference ratings below 3 (i.e., moderately suited). These results can be explained by the prevalence of touchscreens, the increasing availability of smartwatches that incorporate touchscreens, and the intuitive association between controlling the vehicle and the car keys (for which some models[16] incorporate touchscreens as well). An interesting result concerns smartglasses and neural headsets that elicited some interest (2.82 and 2.65, respectively). For the covert zone ❹, for which the PC/laptop and tablet categories were available, ratings of their suitability were high (3.92 and 3.83, respectively).

[16] https://www.bimmer-tech.net/blog/item/118-bmw-display-key

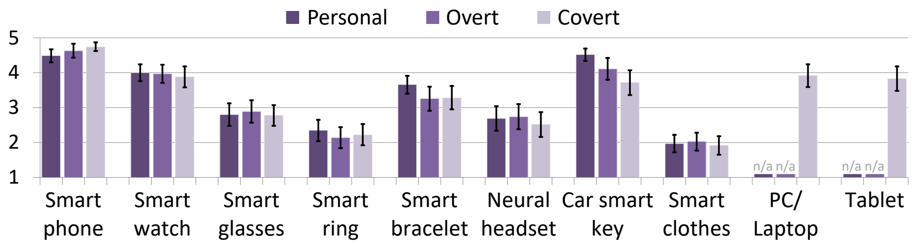

Fig. 7. Preferences for devices to implement outside-the-vehicle interactions.

6 Discussion

In this section, we reflect on the implications of our framework and findings for designing new interactions between drivers and their smart, connected vehicles when the drivers are outside the vehicle in various proximity zones. We also connect our findings to implications from prior work on proxemic interactions [7, 26] regarding interactions in smart environments [27, 34, 62], discuss the dichotomy and complementarity of inside-the-vehicle and outside-the-vehicle interactions, and outline research directions towards pro-active proxemic-aware vehicles.

6.1 Using the Framework and Findings of our Study to Inform Interaction Design for Smart Vehicles

Our framework and study findings provide different benefits and can be used in multiple ways to inform the design of novel outside-the-vehicle interactions. First, the framework can function as a guide to drive design decisions. By widening the focus on previously under-explored interactions outside of smart vehicles, and by articulating the key dimensions (e.g., explicit physical zones, relevant interaction paradigms), this unpacked design space can facilitate the exploration of novel techniques enriching the experience with smart vehicles. For example, practitioners can design different UI layouts for a car smartphone app showing just the relevant functions and hiding others based on the distance between the driver and their car. This design consideration can equally be applied to adaptive user interfaces for wearable devices that feature small screens, such as smartwatches. Second, the framework can also be applied as an analytical lens reflecting on existing interaction techniques for smart vehicles and re-evaluating them in light of the dimensions outlined as part of the framework (e.g., *Where would they be positioned in the design space? How well do the interaction paradigms match the requirements at different physical distance?*), enabling the community to examine at a deeper level of sophistication new opportunities for interaction design for smart vehicles. Third, the particular findings of our study can help identifying promising directions for future work. For example, considering the findings of higher preferences of information about infotainment from the covert zone, or the importance of information about technical state in personal, but also across the other zones, to design optimized interfaces. Fourth, the identified preferences of which devices to use for different outside-the-vehicle interactions showed a wide-spread spectrum across personal/wearable devices in all proximity zones (with only PC/laptop and tablet only matched to interactions at the covert proximity zone). We expect these results to foster more work at the intersection of wearable computing and automotive UIs, where drivers' personal devices turn into readily-available interfaces for controlling the car, such as emergent smartwatches [55], smartglasses [15], and smart rings [24], but also at the intersection of brain-computer interfaces and smart vehicles [14].

6.2 Smart Vehicle Proxemics as Part of Proxemic Interactions

Overall, we argued that smart vehicle proxemics closely relates to the concepts (and can be understood as a part) of proxemic interactions [7, 26]. Operationalizing proxemics in interaction design allows us to better articulate important characteristics relevant for social interaction with devices. The overarching goal is to design proxemic-aware technology for vehicles that — similar to people's natural expectations and everyday use of proxemics — afford varying levels of information access and control of the vehicle that are finely tuned to the different proxemic distances. As the results of our study showed, these expectations are different depending on the distance to the vehicle. And similar to proxemic interactions studied in other contexts — such as interactions with large surfaces or robotics [27, 34, 42, 62, 63] — it is crucial to understand these distance margins not in a *binary* distinction of inside the vehicle and outside it, but rather as a practical means to operate within a continuous interactive space [10] that starts inside the vehicle, surrounds the driver departing their vehicle, and ends in the covert zone. Proxemics [7, 26] functions well in this context as an effective first order approximation of this continuous space, and allowed us to define a framework to more thoroughly investigate the kinds of interactions that leverage the nuances of proxemics for smart vehicle interaction design. At the same time, we expect our framework to be expanded upon in the future with additional dimensions, complementary theories, toolkits, and new empirical findings.

6.3 The Dichotomy and Complementarity of Inside-the-Vehicle and Outside-the-Vehicle Interactions

The design of outside-the-vehicle interactions should be closely matched to any interactions inside the vehicle. In fact, as seen in our full spectrum of physical distance zones, "in-vehicle" is one end point of the continuous distance spectrum. Conceptually, interactions that begin somewhere in any of the other zones (e.g., personal, proximal, distant, or covert) are likely to relate to interactions within the vehicle, potentially at a later point in time. For example, notifications about remaining fuel level being low or about some aspect of the technical status of the vehicle can be delivered to the driver's smartwatch while they are approaching the vehicle and, when inside the vehicle, the driver can make a closer inspection of any issues already signaled to them. Or, interactions performed while inside the vehicle (e.g., stop the engine, pull up the handbrake) can continue while the driver exits the vehicle (e.g., lock the car) and departs from their car (e.g., the car streams statistics about the journey to the driver's smartphone). By looking at the four proximity zones as defining a continuum [10] that goes beyond the dichotomy of inside and outside-the-vehicle input, new opportunities emerge for designing interactions that span a wide range of physical distances, interaction paradigms, and goals. So while we argue that it is important to appropriately unpack the design space of outside-the-vehicle interactions, and that this focus and attention brings up potential for more refined interaction techniques in this space, it is important to emphasize that interactions likely have continuous trajectories across the physical distance zones. At the opposite end of this continuum, outside-the-vehicle interactions expose considerably lower safety concerns compared to interactions with the vehicle while driving, but they also create new potential security risks regarding the remote access to the vehicle by unauthorized individuals getting in the possession of the driver's mobile devices.

6.4 Pro-active Smart Vehicles and Proximity-Awareness

Many interaction techniques suggested within proxemic interactions require devices to have some kind of awareness of the physical distance of a person in relation to the device. This proximity-awareness is then often leveraged by the device to pro-actively initiate certain interactions, for example a whiteboard that reacts to a person's presence [59], or interactive controls that vary their functionality depending on a person's distance [34]. There is a potential to explore such pro-active, proxemic-aware behaviors in the context of smart vehicles: knowing the exact distance of a driver to the car could be leveraged by a person's wearable devices (e.g., smartwatches, smart rings, glasses) or the car directly to best mitigate the information access or control functions. While such proximity-awareness could be based on Bluetooth standards,[11] it could also involve other fine-grained hybrid sensing approaches, incorporating GPS and/or vision data from the car's integrated RGB or depth-sensing cameras. As part of future work, it would be interesting to identify the necessary granularity of such proxemic sensing necessary to best support different kinds of outside-of-vehicle interactions.

7 Conclusion

We introduced smart vehicle proxemics, a framework that structures interactive zones around the smart, connected vehicle and a corresponding conceptual space for outside-the-vehicle interactions. We also reported results from an exploratory user study conducted with drivers to uncover the types of information and system functions for vehicles to control from a distance. With these contributions, we are presenting the scientific community with the first theoretical examination and empirical insights regarding the opportunities offered by outside-the-vehicle interactions, when looking at the smart car as part of a proxemic-oriented smart environment [7, 26].

Future work will look at other measures that are meaningful for smart vehicle proxemics, such as the orientation of the driver with respect to the vehicle, the driver's direction of movement (approaching or departing), relative distance and orientation of other vehicles, pedestrians, and road infrastructure in the context of the Social Vehicle-to-Everything (V2X) Communication Model [45] as well as incorporating drivers' and passengers' roles [9] into our framework, as already hinted in Figure 1. Systematic exploration of proxemic interactions for smart vehicles will foster new designs of interactive techniques and devices, including modern key fobs with functionality that is contextualized and adapted to the physical distance to the vehicle.

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