Expanding V2X with V2DUIs: Distributed User Interfaces for Media Consumption in the Vehicle-to-Everything Era

Laura-Bianca Bilius
MintViz Lab, MANSiD Center, Ştefan cel Mare University of Suceava
Suceava, Romania
laura.bilius@usm.ro

Radu-Daniel Vatavu
MintViz Lab, MANSiD Center, Ştefan cel Mare University of Suceava
Suceava, Romania
radu.vatavu@usm.ro

Jean Vanderdonckt
Louvain Research Institute in Management and Organizations, Université catholique de Louvain
Louvain-la-Neuve, Belgium
jean.vanderdonckt@uclouvain.be

ABSTRACT

Modern in-vehicle infotainment systems connect to drivers' personal digital devices, such as smartphones, to facilitate calls, notifications delivery, and access to online media and resources while driving. This communications process facilitates distributed user interfaces (DUIs) and allows casual in-vehicle interactions. However, such functionalities of modern vehicles still lack the extensive capabilities of state-of-the-art DUIs, which can offer a variety of interaction opportunities through features such as migration, redirection, adaptation, and granularity, among others. In this work, we explore DUIs in the specific context of smart vehicles, and introduce V2DUIs (Vehicle-to-DUIs) as a new addition to the V2X (Vehicle-to-Everything) family of smart vehicle concepts.

CCS CONCEPTS

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

KEYWORDS

Distributed user interfaces, smart vehicles, connected vehicles, V2X, smart environments, ambient intelligence, mobile interactions, wearable interactions, cross-device interactions

ACM Reference Format:

Laura-Bianca Bilius, Radu-Daniel Vatavu, and Jean Vanderdonckt. 2024. Expanding V2X with V2DUIs: Distributed User Interfaces for Media Consumption in the Vehicle-to-Everything Era. In *ACM International Conference on Interactive Media Experiences (IMX '24), June 12–14, 2024, Stockholm, Sweden.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3639701.3663643

1 INTRODUCTION

Smart vehicle technology aims to increase driving safety, optimize traffic efficiency, save energy, and deliver an improved travel experience to the vehicle occupants. Vehicle-to-Everything (V2X) [21, 23,47], a family of communications concepts, technology, and standards for connected vehicles, enables implementation of such desiderata by specifying data sharing between vehicles and surrounding entities, such as other vehicles (V2V), communications networks (V2N), and road infrastructure (V2I). Ultimately, V2X also subsumes communications with pedestrians (V2P) through external human–machine interfaces [15] designed to address the social aspects involving other road users during autonomous driving.

In this context, practical implementations of interactions with smart vehicles largely consist of connecting the driver's smartphone to the in-vehicle system to facilitate phone calls, notifications, and access to online content when inside the vehicle and control of the vehicle when outside it, respectively; see Bilius and Vatavu [8] for a survey of in-vehicle consumption of interactive media, Detjen *et al.* [17] for an overview of in-vehicle interaction design, and Bilius *et al.* [10,11] for a formalization of inside-the-vehicle and outside-the-vehicle interactions, respectively. However, this status quo for smart vehicles has been drastically limited in terms of interaction opportunities for drivers and passengers [9] compared to the state-of-the-art in Distributed User Interfaces (DUIs) [16,20,33,36,42], where a variety of design possibilities are enabled by *migrating* UI elements among different devices, *distributing* parts of the UI on multiple devices, and *integrating* I/O modalities from different devices to increase user efficiency through UI distribution.

The capabilities of state-of-the-art DUIs have not been examined for interactions with smart vehicles, to the best of our knowledge, despite the advantages that DUIs offer in terms of flexibility, versatility, and adaptability to the user, task, and context of use [20,33,42]. However, understanding their potential for smart vehicles would benefit V2X goals for increasing driving safety and enhancing travel experiences through flexible and adaptive interactions across personal digital devices and the vehicle, respectively. To this end, we leverage knowledge from the scientific literature on distributed user interfaces [20,36,42], interactions performed across devices [12] and within smart environments with heterogeneous I/O devices [38], including principles of ambient intelligence [18] developed within the context of smart buildings [3,7] and computer-assisted living environments [43], which we transfer to smart vehicles research.

Our approach consists in adopting the perspective of a smart vehicle as a specific instance of a smart environment [37], where the users' digital devices share data with each other, the cloud, and the in-vehicle infotainment system. In this context, we introduce V2DUIs, a new member of the V2X family of communications concepts for smart vehicles, which leverages the infrastructure of V2X while specifically focusing on the design of UIs that distribute among drivers' and passengers' digital devices and the in-vehicle infotainment system. Specifically, V2DUIs center on interaction possibilities in relation to smart vehicles for which the users are either inside or outside the vehicle [11] and transition across various

IMX '24, June 12–14, 2024, Stockholm, Sweden

ACM ISBN 979-8-4007-0503-8/24/06
https://doi.org/10.1145/3639701.3663643

Figure 1: Example scenarios of V2DUIs, where the in-vehicle infotainment system and users' digital devices enable *multi-device* (top left), *multi-modal* (top right), *multi-user* (top right and bottom left), and *multi-environment* (bottom right) interactions. *Notes:* following Bilius *et al.* [11], we illustrate both inside-the-vehicle and outside-the-vehicle interaction scenarios; from top to bottom and left to right: the smartwatch picks up the driver's mid-air gestures for interacting with the in-vehicle infotainment system; different devices enable different interaction modalities for accessing, transferring, and consuming digital content inside the vehicle; content transfer across passengers; interacting with the vehicle from a different environment.

smart environments, *e.g.*, from smart buildings to smart vehicles and back [7]; see Figure 1 for a few example scenarios of V2DUIs.

2 RELATED WORK

We primarily relate to prior work from the research areas of DUIs, interactions with smart vehicles, and V2X, respectively, at the intersection of which we position our scientific contributions.

2.1 Distributed User Interfaces

A wide scientific literature is available on DUIs and their effective implementation for various application domains. Particularly relevant to the scope of our work are quality properties and models for DUIs, which we explore in the new context of smart vehicle interactions. For example, Elmqvist [20] considered five definitory dimensions across which UI elements can be redirected: *input, output, platform, space*, and *time*. Peñalver *et al.* [34] defined four essential properties for DUIs, *portability*, *decomposability*, *simultaneity*, and *continuity*, which they formalized with a mathematical language of interaction elements. In relation to a transversal model, Vanderdonckt [42] 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." Also, model-based design approaches have been proposed for guiding DUIs development. For example, Melchior *et al.* [31] employed concrete UI models, specification language for distribution primitives operationalized with the extended Backus-Naur form, and a method for modeling DUIs based on distribution scenarios. Demeure *et al.* [16] introduced 4C, a reference model for DUIs with four dimensions—*computation* (*i.e.*, what to distribute?), *communication* (when to distribute?), *coordination* (who implements the distribution?), and *configuration* (*i.e.*, where to distribute?).

Other approaches have focused on frameworks to specify design possibilities for DUIs. For example, Paternò and Santoro [33] proposed a logical framework for multi-device UIs with ten dimensions: *distribution, migration, granularity, generation of the UI, trigger activation, device sharing, timing, interaction modalities, adaptation,* and *architecture*. In this framework, a DUI can be generated at design time or run-time, its granularity specifies the UI elements that are being distributed, and the UI can adapt in terms of scaling, transduction, and transformation. Sanctorum and Signer [36] proposed a 2D interaction space organized along the *physical location* of the system and its components (*i.e.*, table-level, room-level, network connection to a server, and anywhere) and the *granularity* of the distribution (*i.e.*, UI+data and UI+data+UI elements). For example, room-level DUIs distribute across devices to make an entire room interactive. To the best of our knowledge, the exploration of such state-of-the-art DUI concepts has been lacking for smart vehicle interactions, likely due to the absence of a formalization of DUIs in this specific context, an aspect that we address in Section 3.

2.2 Smart Vehicle Interactions and V2X

Smart vehicles interact with their internal environment, *i.e.*, the driver, passengers, and digital devices [17,24], as well as the external environment, *e.g.*, other vehicles, road infrastructure, networks, and pedestrians [2,21,23,29]. To this end, the 3GPP Technical Specification of V2X service requirements [21] outlines four types of V2X applications—Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N)—to enable cooperative awareness for vehicles that provide intelligent services to their users. For instance, V2V applications expect vehicles located in proximity to each other to exchange information; V2I enables vehicles to receive data broadcast from the intelligent transportation system, such as speed limits, weather conditions, and accident reports; V2N applications use cellular networks to communicate with servers constituting the V2X management system; and V2P applications exchange information between vehicles and pedestrians, *e.g.*, warnings to pedestrians but also to vehicles about vulnerable road users. Inside the vehicle, data can be exchanged between the driver's personal devices and the in-vehicle infotainment and navigation system.

Several frameworks have been proposed for the design of inside and outside-the-vehicle interactions. For example, Detjen *et al.* [17] overviewed input modalities (emotions, eye gaze, mid-air gestures, speech) and output modalities (visual, auditory) for in-vehicle interaction; Kern and Schmidt [24] considered the position of devices inside the vehicle (*e.g.*, windshield, center stack, periphery) as a design dimension for driver-based automotive UIs; Vatavu *et al.* [44] leveraged gesture input performed on the driver's seat for interactive media consumption experiences inside the vehicle; Colley *et al.* [14] discussed external vehicle displays; and Bilius *et al.* [11] introduced a conceptual framework to operationalize proxemic interactions with smart vehicles. We leverage some of these frameworks in Section 3 to contextualize our new concept of V2DUIs for smart vehicle interactions.

In this context, human factors design principles for driver-vehicle UIs [13] include many aspects, such as suitable feedback modalities, design of controls, driver information needs, system integration, and performance metrics [13], driver attention capabilities [26], and drivers' and passengers' preferences for interactions with the vehicle [9]. For example, Kun *et al.* [26] designed Project54, an integrated system featuring two user interfaces for all of the in-vehicle electronic devices, displays, and input systems competing for the driver's attention. Bilius and Vatavu [9] examined preferences of gesture and voice commands for in-vehicle interactions. A recent work [7] proposed multi-environment interactions involving smart vehicles and smart buildings, where both represent instances of smart environments transitioned by mobile users.

3 V2DUIs: VEHICLE-TO-DISTRIBUTED USER INTERFACES

We introduce V2DUIs, a new concept that we characterize with specific quality properties identified by adapting design principles for DUIs [20,31,33,36,42] and inside-the-vehicle and outside-the-vehicle interactions [9,11,14,17,24], respectively. Our operational definition of V2DUIs is DUIs that integrate interactive systems from the smart vehicle, *e.g.*, the in-vehicle infotainment system, during the distribution of UI elements, I/O modalities, and tasks across drivers and passengers, their digital devices, and possible environments, including outside-the-vehicle, such as a smart building [7]. We start our discussion with a contextualization of V2DUIs.

3.1 Context for V2DUIs

DUIs enable users to engage in distributed tasks on different devices at different locations and moments in time [20,42]. In the following, we capitalize on state-of-the-art models from the DUI scientific literature, overviewed in Subsection 2.1, to position V2DUIs as a specific instance of DUIs in a new application domain and context of use with distinctive quality characteristics; see Figures 2a-2c. We also capitalize on existing design spaces for smart vehicle interactions to integrate DUIs; see Figures 2d-2g.

We begin our exploration with Elmqvist's [20] five definitory dimensions and Vanderdonckt's [42] transversal model for generic DUIs due to their generality and adaptable nature across different contexts of use; see Figures 2a and 2b. According to these models, in-vehicle interactions distribute across multiple devices, displays, and platforms, which are co-located and synchronously operated.

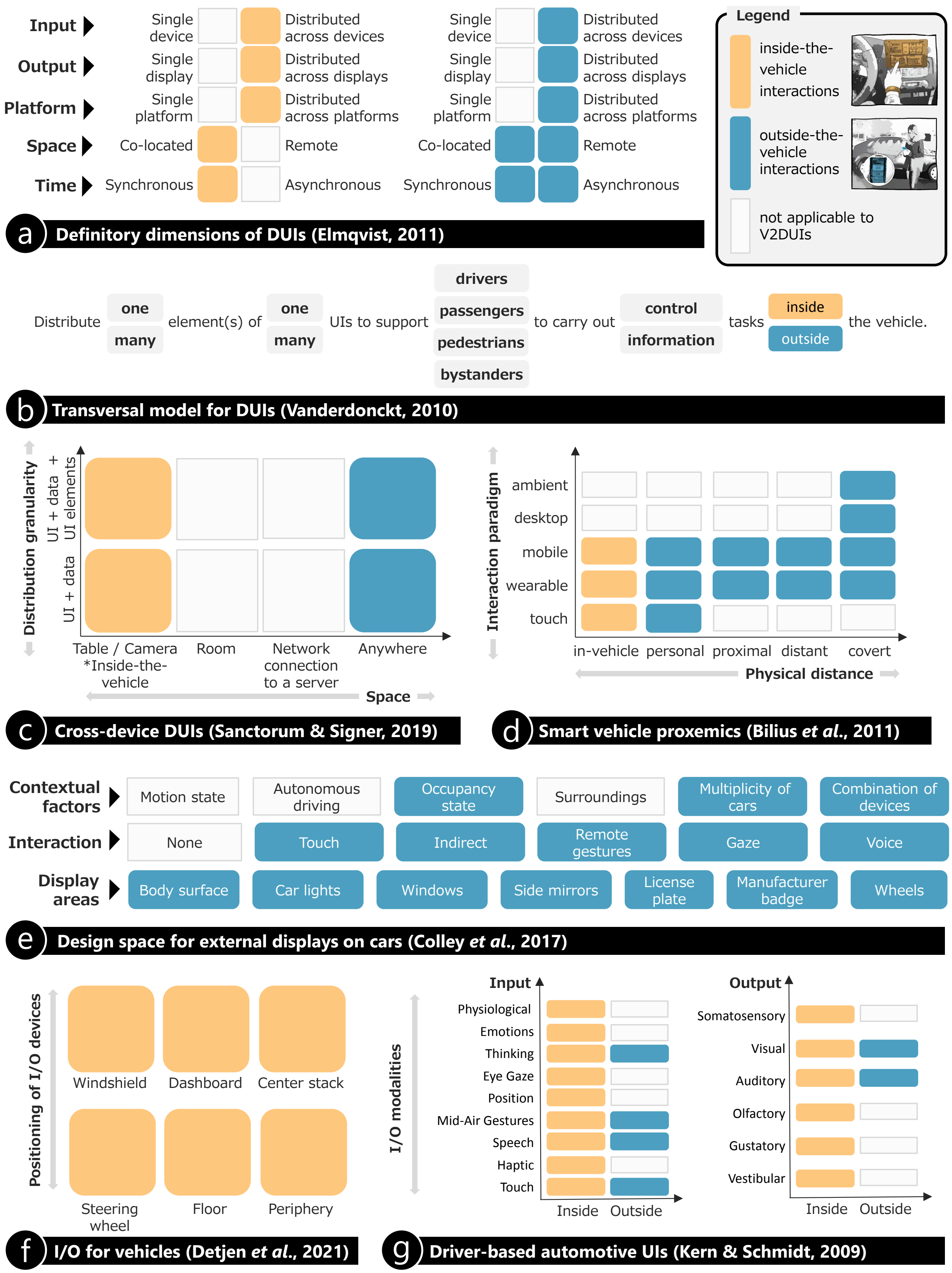

Figure 2: Contextualization of V2DUIs using several conceptual and design frameworks for DUIs (a-c) [20,36,42] and interactions with vehicles (d-g) [11,14,17,24]. Note the *multi-environment* orientation of V2DUIs with distinctive design possibilities for in-vehicle (orange color) and outside-the-vehicle (blue) interactions; Subsection 3.2 presents other quality properties.

However, outside-the-vehicle interactions distribute differently in terms of space and time by enabling both co-located (*i.e.*, the user is near the vehicle) and remote operation (*i.e.*, the user is in the covert interaction region, according to [11]) as well as both synchronous and asynchronous interactions. Regarding the latter, an example of an asynchronous interaction would be the driver summoning their autonomous vehicle, for which the response, represented by the vehicle arriving at the specified location, would take place at a later moment. This model is conveniently flexible to showcase the versatility of DUIs, which we adopt for the specific users and environments of V2DUIs in relation to a vehicle. Furthermore, Vanderdonckt's [42] model enables us to refine the user category according to the key actors in V2X, *i.e.*, drivers, passengers, pedestrians, and bystanders, as well as to discriminate between control and information tasks during interactions with the smart vehicle. For example, the driver has complete control over the in-vehicle infotainment system, while the passengers have access to specific information, such as details about the travel route. More refinements to these dimensions are possible with Sanctorum and Signer's [36] cross-device model of DUIs; see Figure 2c. In this model, V2DUIs position in the *table/camera* region because of the restricted space for drivers to engage in in-vehicle interactions, characterized by the seated posture, limited space for reaching legs and arms, and so forth, while outside-the-vehicle interactions fall within the much broader space of the *anywhere* region. The limited space poses design challenges for effective interaction enabled by V2DUIs, where specific parts of the in-vehicle environment, such as the steering wheel [5] or the seat [44], play key roles for supporting the interaction.

The dimensional aspects encompassing input, output, and spatial elements within these DUI models enable us to engage in conceptual transitions towards frameworks for smart vehicle interactions. For example, Bilius *et al.*'s [11] vehicle proxemics framework is useful to characterize diverse possibilities for distributing UI elements, I/O modalities, and tasks in V2DUIs among interaction paradigms (*i.e.*, from touch to wearable, mobile, desktop, and ambient) according to the driver's physical distance to their vehicle; see Figure 2d. For example, when the driver is in the *personal zone* at about 1m from the vehicle, a wearable device featuring short-range Bluetooth or NFC communications, such as a smart ring, can be used to gain access to the vehicle. Furthermore, when in the *covert zone*, where the vehicle is outside the driver's view, an ambient device can inform about the security status of the parked vehicle [10]. For other user categories, outside-the-vehicle interactions repurpose the vehicle as a public ambient display [14], *e.g.*, the body surfaces and windows of a parked vehicle turn into convenient displays for pedestrians and passersby; see Figure 2e for contextual factors, interaction modalities, and display areas from Colley *et al.* 's [14] design space for external displays on cars that are relevant for V2DUIs. Finally, in-vehicle interactions have been formalized in terms of I/O modalities [17] and physical location of controls, devices, and systems from inside the vehicle [24]. Figures 2f and 2g illustrate these dimensions for V2DUIs as well as a possible extension to outside-the-vehicle interactions. When outside the vehicle, V2DUIs can leverage specific elements and parts of other smart environments, such as smart rooms and buildings for multi-environment interactions; see [7] for a formalization of the concept within the context of ubiquitous computing and [10] for application scenarios.

Our exploration so far has revealed V2DUIs fitting into various frameworks from the scientific literature on DUIs and smart vehicle interactions as they merge properties of both areas as well as enablers of multi-environment interactions. However, we also uncovered how V2DUIs present distinctive features, *e.g.*, multi-environment operation inside and outside the vehicle, more challenging to describe with existing DUI frameworks. Next, we distill these features into four quality properties specific to V2DUIs.

3.2 Quality Properties of V2DUIs

Based on our previous analysis of DUI frameworks [20,31,34,42] and V2X communications requirements for smart vehicles [21,23,29,47], we highlight two guiding principles for V2DUIs design, as follows:

(P_1) *Smart vehicle orientation.* Smart vehicles are equipped with various sensors, displays, and systems and interact with other vehicles, road infrastructure, communications networks, and pedestrians. Following a perspective from Tonnis *et al.* [41], vehicles are "complex computer systems with very particular input and output devices and mobile functionality." Following a perspective from Schipor and Vatavu [37], "the smart, connected car [is] a specific type of a smart environment." In this context, our principle of *smart vehicle orientation* specifies that the technology integrated into smart vehicles, *e.g.*, touchscreens, Bluetooth, etc., can be readily leveraged for V2DUIs, *i.e.*, V2X infrastructure supports V2DUIs.

(P_2) *UI distribution orientation.* According to this generic principle of DUIs, users are more effective if tasks can be ported, composed, or distributed across the elements of the context of use. Applied to smart vehicles, this principle incorporates Peñalver *et al.*'s [34] simultaneity and continuity essential characteristics of a DUI. By being *distribution oriented*, V2DUIs can be more than the sum of the individual devices they integrate and deliver new functionality to end users, *e.g.*, the ability to switch between I/O modalities and to combine different modalities of the individual components. New functionality emerges in V2DUIs and, therefore, within the V2X paradigm, as a consequence of UI distribution.

According to these two guiding principles, the following four quality properties (Q_1 to Q_4) specify how the various elements of a UI can be distributed in V2DUIs: across *devices* (*e.g.*, the driver's personal devices), across *I/O modalities* (*e.g.*, information about the driver's heart rate, sensed by a smartwatch, is delivered to the in-vehicle system), across *users* (*e.g.*, the passenger employs their smartphone to upload music to the in-vehicle system), and across *environments* (represented by a continuous interaction space, where interactions are performed inside and outside the vehicle, unifying the distinctive environments of smart vehicles and smart buildings):

(Q_1) *Multi-device operation.* V2DUIs enable multiple devices to be employed for both input and output. Since different devices may run different platforms and feature different mechanisms for feedback, we integrate the multi-platform and multi-monitor properties from Peñalver *et al.* [34] and the multi-monitor, multi-platform, and multi-display usage properties from Vanderdonckt [42] under this one category.[1] For

[1] Vanderdonckt [42] also consider that multi-device subsumes multi-platform.

example, V2DUIs should adapt to various devices that may have different form factors, display sizes, communications capabilities, sensors, and operating systems. This quality property is convenient to accommodate integration of a variety of mobile and wearable devices, such as smartphones [10,25,39], smartwatches [6], tablets [35], smartglasses [1], smart earbuds [46], smart rings [22], and so forth, for interactions with vehicles. From this perspective, V2DUIs implement UIs for heterogeneous smart environments [38].

(Q_2) *Multi-modality operation.* Multi-modal interaction implies the use of various input modalities (*e.g.*, touch [19], voice [4], on-wheel input [27], mid-air gestures [9,32]) and output modalities (*e.g.*, visual, audio [40], haptic, olfactory [17]) to increase users' effectiveness and efficiency when interacting with computer systems. By means of this quality property, V2DUIs address aspects of driving safety by enabling drivers to switch between I/O modalities as need, without taking their hands off the wheel and eyes off the road.

(Q_3) *Multi-user operation.* V2DUIs enable interactions for various user categories, including drivers [17,24], passengers [9], and bystanders [14], by distributing UI elements on each user's devices. Noteworthy, the majority of research on interactions with vehicles has focused on drivers, while passengers have been little addressed [9]. Thus, *multi-user operation* is also an opportunity for more research in this direction.

(Q_4) *Multi-environment operation.* V2DUIs enable interactions with the vehicle while the users are inside the vehicle [4,19], near the vehicle in its immediate vicinity, *e.g.*, a gesture performed near the car opens the trunk [22], or at various distances from the vehicle, *e.g.*, an ambient device delivers a notification from the vehicle [11]. Depending on the specific environment type, various I/O modalities may be available [10] as well as distinct opportunities for personalizing interactions according to the user and the environment [7].

4 CONCLUSION AND FUTURE WORK

As in-vehicle environments become more complex with the integration of more sensors and systems, and vehicles advance in their V2X capabilities, scaling the user experience of smart vehicle interactions becomes key. In this paper, we proposed V2DUIs, a novel concept grounded in both DUIs and V2X, to distribute smart vehicle functionality and operation across digital devices, users, and environments. In future work, we envision consolidating the V2DUIs dimensions into a design space for explicitly exploring design possibilities [28]. For example, this space can be represented by the multidimensional combination, composition, and interaction of input dimensions (*e.g.*, number of input devices and sensors, interaction modalities, and their relationships) and corresponding output dimensions (*e.g.*, number of display devices) to support V2DUIs design and engineering. To this end, we believe that V2DUIs can be readily attained with conventional technology, such as web-based protocols [10,11,37]. Furthermore, understanding users' preferences for distributing interactions across multiple devices through participatory design studies [45] will enable more insights of cross-device use styles and patterns [12] inside and outside the vehicle. Additional formalization, such as based on distribution primitives [30], will enable further development of V2DUIs. To this end, we hope that V2DUIs will inspire innovations in how interactive media consumption experiences involving smart vehicles, personal digital devices, and various environments will look like in the future.

ACKNOWLEDGMENTS

This work was supported by the NetZeRoCities Competence Center, funded by European Union-NextGenerationEU and Romanian Government, under the National Recovery and Resilience Plan for Romania, contract no. 760007/30.12.2022 with the Romanian Ministry of Research, Innovation and Digitalization through the specific research projects P3, Smart and sustainable buildings and P4, Smart mobility and infrastructure.

REFERENCES

[1] Adrian Aiordăchioae, Radu-Daniel Vatavu, and Dorin-Mircea Popovici. 2019. A Design Space for Vehicular Lifelogging to Support Creation of Digital Content in Connected Cars. In *Proceedings of the ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '19)*. ACM, New York, NY, USA, Article 9, 6 pages. https://doi.org/10.1145/3319499.3328234

[2] Ammar Al-Taie, Graham Wilson, Frank Pollick, and Stephen Anthony Brewster. 2023. Pimp My Ride: Designing Versatile EHMIs for Cyclists. In *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '23)*. ACM, New York, NY, USA, 213–223. https://doi.org/10.1145/3580585.3607161

[3] Wael Alsafery, Omer Rana, and Charith Perera. 2023. Sensing within Smart Buildings: A Survey. *ACM Comput. Surv.* 55, 13s, Article 297 (jul 2023), 35 pages. https://doi.org/10.1145/3596600

[4] Leonardo Angelini, Jürgen Baumgartner, Francesco Carrino, Stefano Carrino, Maurizio Caon, Omar Abou Khaled, Jürgen Sauer, Denis Lalanne, Elena Mugellini, and Andreas Sonderegger. 2016. Comparing Gesture, Speech and Touch Interaction Modalities for In-Vehicle Infotainment Systems. In *Actes de la 28ième Conference Francophone sur l'Interaction Homme-Machine (IHM '16)*. ACM, New York, NY, USA, 188–196. https://doi.org/10.1145/3004107.3004118

[5] Leonardo Angelini, Francesco Carrino, Stefano Carrino, Maurizio Caon, Omar Abou Khaled, Jürgen Baumgartner, Andreas Sonderegger, Denis Lalanne, and Elena Mugellini. 2014. Gesturing on the Steering Wheel: A User-Elicited Taxonomy. In *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '14)*. ACM, New York, NY, USA, 1–8. https://doi.org/10.1145/2667317.2667414

[6] Laura-Bianca Bilius. 2020. A Smartwatch-based User Interface for In-Vehicle Interactions. In *Proceedings of the 15th International Conference on Development and Application Systems (DAS '20)*. IEEE, USA, 169–172. https://doi.org/10.1109/DAS49615.2020.9108911

[7] Laura-Bianca Bilius, Alexandru-Tudor Andrei, and Radu-Daniel Vatavu. 2024. From Smart Buildings to Smart Vehicles: Mobile User Interfaces for Multi-Environment Interactions. In *Proceedings of the 17th International Conference on Development and Application Systems (DAS '24)*. IEEE, USA, 4 pages.

[8] Laura-Bianca Bilius and Radu-Daniel Vatavu. 2020. A Synopsis of Input Modalities for In-Vehicle Infotainment and Consumption of Interactive Media. In *Proceedings of the ACM International Conference on Interactive Media Experiences (IMX '20)*. ACM, New York, NY, USA, 195–199. https://doi.org/10.1145/3391614.3399400

[9] Laura-Bianca Bilius and Radu-Daniel Vatavu. 2021. A Multistudy Investigation of Drivers and Passengers' Gesture and Voice Input Preferences for In-Vehicle Interactions. *Journal of Intelligent Transportation Systems* 25 (2021), 197–220. https://doi.org/10.1080/15472450.2020.1846127

[10] Laura-Bianca Bilius, Radu-Daniel Vatavu, and Nicolai Marquardt. 2021. Exploring Application Opportunities for Smart Vehicles in the Continuous Interaction Space Inside and Outside the Vehicle. In *Human-Computer Interaction (INTERACT '21)*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen (Eds.). Springer International Publishing, Cham, 140–149. http://dx.doi.org/10.1007/978-3-030-85616-8_10

[11] Laura-Bianca Bilius, Radu-Daniel Vatavu, and Nicolai Marquardt. 2021. Smart Vehicle Proxemics: A Conceptual Framework Operationalizing Proxemics in the Context of Outside-the-Vehicle Interactions. In *Human-Computer Interaction (INTERACT '21)*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen (Eds.). Springer International Publishing, Cham, 150–171. http://dx.doi.org/10.1007/978-3-030-85616-8_11

[12] Frederik Brudy, Christian Holz, Roman Rädle, Chi-Jui Wu, Steven Houben, Clemens Nylandsted Klokmose, and Nicolai Marquardt. 2019. Cross-Device Taxonomy: Survey, Opportunities and Challenges of Interactions Spanning Across Multiple Devices. In *Proceedings of the 2019 CHI Conference on Human*

Factors in Computing Systems (CHI '19). ACM, New York, NY, USA, 28 pages. https://doi.org/10.1145/3290605.3300792

[13] John L. Campbell, Zachary R. Doerzaph, Christian M. Richard, and L. Paige Bacon. 2014. Human Factors Design Principles for the Driver-Vehicle Interface (DVI). In *Adjunct Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '14)*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/2667239.2667305

[14] Ashley Colley, Jonna Häkkilä, Bastian Pfleging, and Florian Alt. 2017. A Design Space for External Displays on Cars. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct (AutomotiveUI '17)*. ACM, New York, NY, USA, 146–151. https://doi.org/10.1145/3131726.3131760

[15] Joost de Winter and Dimitra Dodou. 2022. External Human–Machine Interfaces: Gimmick or Necessity? *Transportation Research Interdisciplinary Perspectives* 15 (2022), 100643. https://doi.org/10.1016/j.trip.2022.100643

[16] Alexandre Demeure, Jean-Sébastien Sottet, Gaëlle Calvary, Joëlle Coutaz, Vincent Ganneau, and Jean Vanderdonckt. 2008. The 4C Reference Model for Distributed User Interfaces. In *Proceedings of the 4th Int. Conference on Autonomic and Autonomous Systems*. IEEE, USA, 61–69. http://dx.doi.org/10.1109/ICAS.2008.34

[17] Henrik Detjen, Sarah Faltaous, Bastian Pfleging, Stefan Geisler, and Stefan Schneegass. 2021. How to Increase Automated Vehicles' Acceptance through In-Vehicle Interaction Design: A Review. *International Journal of Human–Computer Interaction* 37, 4 (2021), 308–330. https://doi.org/10.1080/10447318.2020.1860517

[18] Rob Dunne, Tim Morris, and Simon Harper. 2021. A Survey of Ambient Intelligence. *ACM Comput. Surv.* 54, 4, Article 73 (may 2021), 27 pages. https://doi.org/10.1145/3447242

[19] Ronald Ecker, Verena Broy, Andreas Butz, and Alexander De Luca. 2009. PieTouch: A Direct Touch Gesture Interface for Interacting with in-Vehicle Information Systems. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '09)*. ACM, New York, NY, USA, Article 22, 10 pages. https://doi.org/10.1145/1613858.1613887

[20] Niklas Elmqvist. 2011. Distributed User Interfaces: State of the Art. In *Distributed User Interfaces: Designing Interfaces for the Distributed Ecosystem*, José A. Gallud, Ricardo Tesoriero, and Victor M.R. Penichet (Eds.). Human-Computer Interaction Series. Springer, London, 1–12. https://doi.org/10.1007/978-1-4471-2271-5_1

[21] European Telecommunications Standards Institute (ETSI). 2020. *LTE; Service requirements for V2X services (3GPP TS 22.185 version 16.0.0 Release 16)*. Technical Report. European Telecommunications Standards Institute. https://www.etsi.org/deliver/etsi_ts/122100_122199/122185/16.00.00_60/ts_122185v160000p.pdf

[22] Bogdan-Florin Gheran and Radu-Daniel Vatavu. 2020. From Controls on the Steering Wheel to Controls on the Finger: Using Smart Rings for In-Vehicle Interactions. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference (DIS' 20 Companion)*. ACM, New York, NY, USA, 299–304. https://doi.org/10.1145/3393914.3395851

[23] IEEE. 2010. IEEE 802.11p-2010 - IEEE Standard for Information technology–Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. https://standards.ieee.org/standard/802_11p-2010.html

[24] Dagmar Kern and Albrecht Schmidt. 2009. Design Space for Driver-Based Automotive User Interfaces. In *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '09)*. ACM, New York, NY, USA, 3–10. https://doi.org/10.1145/1620509.1620511

[25] B. Kirthika, M. Saiswathika, and G. Nivya Sree. 2016. A Review on Smart Watch. *International Journal of Trend in Research and Development (IJTRD)* 3 (2016), 3 pages. Issue 3. http://www.ijtrd.com/ViewFullText.aspx?Id=3949

[26] Andrew L. Kun, W. Thomas Miller, and William H. Lenharth. 2004. Computers in Police Cruisers. *IEEE Pervasive Computing* 3, 4 (2004), 34–41. https://doi.org/10.1109/MPRV.2004.3

[27] Sang Hun Lee, Se-One Yoon, and Jae Hoon Shin. 2015. On-Wheel Finger Gesture Control for in-Vehicle Systems on Central Consoles. In *Adjunct Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '15)*. ACM, New York, NY, USA, 94–99. https://doi.org/10.1145/2809730.2809739

[28] Sophie Lepreux, Jean Vanderdonckt, and Benjamin Michotte. 2006. Visual Design of User Interfaces by (De)composition. In *Proceedings of the 13th International Workshop on Interactive Systems. Design, Specification, and Verification (Lecture Notes in Computer Science, Vol. 4323)*. Springer, Berlin, Heidelberg, 157–170. https://doi.org/10.1007/978-3-540-69554-7_13

[29] Ning Lu, Nan Cheng, Ning Zhang, Xuemin Shen, and Jon W. Mark. 2014. Connected Vehicles: Solutions and Challenges. *IEEE Internet of Things Journal* 1, 4 (2014), 289–299. https://doi.org/10.1109/JIOT.2014.2327587

[30] Jérémie Melchior, Jean Vanderdonckt, and Peter Van Roy. 2011. Distribution Primitives for Distributed User Interfaces. In *Distributed User Interfaces - Designing Interfaces for the Distributed Ecosystem*. Springer, London, 23–31. https://doi.org/10.1007/978-1-4471-2271-5_3

[31] Jérémie Melchior, Jean Vanderdonckt, and Peter Van Roy. 2011. A Model-Based Approach for Distributed User Interfaces. In *Proceedings of the 3rd ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '11)*. ACM, New York, NY, USA, 11–20. https://doi.org/10.1145/1996461.1996488

[32] Eshed Ohn-Bar, Cuong Tran, and Mohan Trivedi. 2012. Hand Gesture-Based Visual User Interface for Infotainment. In *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '12)*. ACM, New York, NY, USA, 111–115. https://doi.org/10.1145/2390256.2390274

[33] Fabio Paternò and Carmen Santoro. 2012. A Logical Framework for Multi-Device User Interfaces. In *Proceedings of the 4th ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '12)*. ACM, USA, 45–50. https://doi.org/10.1145/2305484.2305494

[34] A. Peñalver, J.J. López-Espín, J.A. Gallud, E. Lazcorreta, and F. Botella. 2011. Distributed User Interfaces: Specification of Essential Properties. In *Distributed User Interfaces*, J. Gallud, R. Tesoriero, and V. Penichet (Eds.). Springer, London, 13–21. https://doi.org/10.1007/978-1-4471-2271-5_2

[35] Ken Pfeuffer and Hans Gellersen. 2016. Gaze and Touch Interaction on Tablets. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 301–311. https://doi.org/10.1145/2984511.2984514

[36] Audrey Sanctorum and Beat Signer. 2019. Towards End-User Development of Distributed User Interfaces. *Universal Access in the Information Society* 18 (2019), 785–799. https://doi.org/10.1007/s10209-017-0601-5

[37] Ovidiu-Andrei Schipor and Radu-Daniel Vatavu. 2021. Empirical Results for High-definition Video and Augmented Reality Content Delivery in Hyper-connected Cars. *Interacting with Computers* 33, 1 (2021), 3–16. https://doi.org/10.1093/iwcomp/iwaa025

[38] Ovidiu-Andrei Schipor, Radu-Daniel Vatavu, and Jean Vanderdonckt. 2019. Euphoria: A Scalable, Event-Driven Architecture for Designing Interactions Across Heterogeneous Devices in Smart Environments. *Information and Software Technology* 109 (2019), 43–59. https://doi.org/10.1016/j.infsof.2019.01.006

[39] Gurdit Singh, Divya Bansal, and Sanjeev Sofat. 2017. A Smartphone Based Technique to Monitor Driving Behavior Using DTW and Crowdsensing. *Perv. Mob. Comp.* 40 (2017), 56–70. https://doi.org/10.1016/j.pmcj.2017.06.003

[40] Moustafa Tabbarah, Yusheng Cao, Ahmad Abu Shamat, Ziming Fang, Lingyu Li, and Myounghoon Jeon. 2023. Novel In-Vehicle Gesture Interactions: Design and Evaluation of Auditory Displays and Menu Generation Interfaces. In *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '23)*. ACM, New York, NY, USA, 224–233. https://doi.org/10.1145/3580585.3607164

[41] M. Tonnis, V. Broy, and G. Klinker. 2006. A Survey of Challenges Related to the Design of 3D User Interfaces for Car Drivers. In *Proceedings of 3D User Interfaces (3DUI '06)*. IEEE, USA, 127–134. https://doi.org/10.1109/VR.2006.19

[42] Jean Vanderdonckt. 2010. Distributed User Interfaces: How to Distribute User Interface Elements across Users, Platforms, and Environments. In *Proc. of the 11th Congreso Internacional de Interacción Persona-Ordenador Interacción*. AIPO, Valencia, 20–32. http://www.usixml.org/en/vanderdonckt-j-distributed-user-interfaces-how-to-distribute-user-interface-elements-across-users-platforms-and-environm.html?IDC=465&IDD=1433

[43] Radu-Daniel Vatavu. 2022. Are Ambient Intelligence and Augmented Reality Two Sides of the Same Coin? Implications for Human-Computer Interaction. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA '22)*. ACM, New York, NY, USA, Article 362, 8 pages. https://doi.org/10.1145/3491101.3519710

[44] Radu-Daniel Vatavu, Laura-Bianca Bilius, Alexandru-Tudor Andrei, Mihail Terenti, Adrian-Vasile Catană, and Alexandru-Ionuţ Şiean. 2024. ChairMX: On-Chair Input for Interactive Media Consumption Experiences for Everyone, Everywhere. In *Proceedings of the ACM International Conference on Interactive Media Experiences (IMX '24)*. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3639701.3661090

[45] Santiago Villarreal-Narvaez, Arthur Sluÿters, Jean Vanderdonckt, and Radu-Daniel Vatavu. 2024. Brave New GES World: A Systematic Literature Review of Gestures and Referents in Gesture Elicitation Studies. *ACM Comput. Surv.* 56, 5, Article 128 (jan 2024), 55 pages. https://doi.org/10.1145/3636458

[46] Xuhai Xu, Haitian Shi, Xin Yi, WenJia Liu, Yukang Yan, Yuanchun Shi, Alex Mariakakis, Jennifer Mankoff, and Anind K. Dey. 2020. EarBuddy: Enabling On-Face Interaction via Wireless Earbuds. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376836

[47] Li Zhao, Jiayi Fang, Jinling Hu, Yuanyuan Li, Lin Lin, Yan Shi, and Chenxin Li. 2018. The Performance Comparison of LTE-V2X and IEEE 802.11p. In *Proceedings of the IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE, USA, 1–5. https://doi.org/10.1109/VTCSpring.2018.8417813