Towards a Design Space for External Communication of Autonomous Vehicles

Mark Colley
Institute of Media Informatics
Ulm University, Germany
mark.colley@uni-ulm.de

Enrico Rukzio
Institute of Media Informatics
Ulm University, Germany
enrico.rukzio@uni-ulm.de

CHI '20 Extended Abstracts, April 25–30, 2020, Honolulu, HI, USA.

ACM ISBN 978-1-4503-6819-3/20/04.
http://dx.doi.org/10.1145/3334480.3382844

Abstract
Autonomous vehicles are about to enter the mass market and with it a complex socio-technical system including vulnerable road users such as pedestrians and cyclists. Communication from autonomous vehicles to vulnerable road users can ease the introduction of and aids in understanding the intention of these. Various modalities and messages to communicate have been proposed and evaluated. However, a concise design space building on work from communication theory is yet to be presented. Therefore, we want to share our work on such a design space consisting of **4** dimensions: *Message Type*, *Modality*, *Locus*, and *Communication Participants*.

Author Keywords
Autonomous vehicles; self-driving vehicles; intention communication; external communication; design space.

CCS Concepts
•**Human-centered computing** → *HCI theory, concepts and models;*

Introduction

Autonomous vehicles (AVs) are expected to change interaction between pedestrians and vehicles [14]. There is no need for a human driver to be present in AVs. Interpersonal communication for situations, in which people today rely on eye-contact or gestures [29] will therefore be even more challenging. Recent research projects aim to overcome these upcoming challenges through external communication to vulnerable road users (VRUs) such as displays [15], LED strips [15, 23], movement patterns [39], projections [1], auditory or tactile cues [25], combinations thereof [25], and enhancement of the infrastructure [35].

Researcher struggle whether and when such communication is necessary [26] and which modality and technology to use given the numerous aforementioned opportunities.

We present a design space for such external communication of AVs based on research on communication theories of Berlo [7] and DeVito [11]. The proposed design space consists of **4** dimensions (Message Type, Modality, Locus, Communication Participants; see Sidebar and Section Dimensions and Values). Current work has been classified and research gaps are named. The design space shows that current external Human-Machine Interfaces (eHMIs) mainly are of instructional or advisory nature, answers e.g. for inquiries such as “Can I cross?” are unexplored.

Background

This work builds on research in the fields *Design Spaces in HCI*, *Communication Theory*, and *External Communication of AVs*.

Design Spaces in HCI

In Human-Computer Interaction (HCI) research, taxonomies [16] and design spaces [18] allow for the exploration of potential interaction possibilities. They also aid in understanding current as well as upcoming technologies (e.g., shape changing interfaces [20] or external communication of AVs [25]). Especially taxonomies enable researchers to systematize knowledge about interaction techniques and input devices [16].

Therefore, creating a design space about external communication of AVs is a first step to understand current trends and to uncover unknown potential.

Communication Theory & Models

Communication theory is a multidisciplinary research field concerned with intra- and interpersonal communication. Starting in 1920, various models have been proposed. The three most commonly described models are *Linear*, *Interactional*, and *Transactional*. Shannon and Weaver introduced the first linear model in 1949 [34] with no feedback or response mechanisms. In interactional models, participants alternate positions as sender and receiver [33], e.g. Sender-Message-Channel-Receiver (SMCR) Model of Communication [7]. This model mainly has four components to describe communication: sender, message, channel, and receiver. Transactional models involve other factors such as cultural or social context in the communication concept [4], e.g. DeVito’s interactive model [11]. Compared to the SMCR-model, this model includes context, feedback, and noise as factors. Rothwell explains the concept of noise and divides it into four categories: (1) physical noise or external noise such as poorly heated rooms or startling sounds, (2) physiological noise such as sweaty palms or speech anxiety, (3) psychological noise means that your preconception alters the way one talks to another, e.g., with a foreigner or a child and (4) semantic noise which is using confusing or distracting word choices [31]. Additionally, there is the constructionist view on communication, as described by Lanham [21]. In this view, the meaning of a message is not solely dependent on the sender but also on the receiver. This means that the knowledge and views of the receiver play an important role in unveiling the meaning of the sender. Trenholm [36] put this in the in the context of entire cultures: “communication is a process whereby people in groups, using the tools provided by their culture, create collective representations of reality”.

External Communication of AVs

An overview on vehicle-pedestrian interaction with both traditional and AVs is given by Rasouli and Tsotsos [30] with special regard to communication modalities and messages. Various aspects of external concepts of AVs have been investigated in literature: Rouchitsas and Alm [32] focus on empirical work in which a clear benefit from these concepts was found. Colley et al. [10] focused on the used modality in the concepts, evaluating 29 concepts in a thorough survey finding that visual concepts were most prevalent. Industrial concepts were analyzed by Bazilinskyy et al. [5] with focus on visual features such as color. These include projections and LED displays (Mercedes Benz F 015 [6]) or abstractions reminiscent of a face (VW Sedric [37]).

Differentiation to Other Design Spaces

Design spaces for various aspects of external communication of AVs have been proposed. Colley et al. [9] showed where external displays can be attached to a vehicle. Löcken et al. [22] classified the interaction concepts under investigation into four categories: visual only, visual plus acoustic, anthropomorphic, and concepts including infrastructure. This resembles the dimensions *Modality* and *Locus*. They further distinguished each category based on the complexity of the information presented.

Mahadevan et al. [25] employed a method called PICTIVE [2] to elicit possibilities for external communication of AVs. They propose a design space with the dimensions *Cue category* (Visual, Auditory and Physical) and (not explicitly stated) *Locus* of the communication (Vehicle-only, Vehicle and Street, Vehicle and Pedestrian, Mixed). There are two concerns regarding this proposal and the classification: The physical cue seems mixed as “Car lowering/raising” is actually a visual stimulus. The nomenclature of physical could also be changed to tactile having a clear foundation in research on senses. *Mixed* locus allows for an ambiguous classification of proposals. We argue that this category should be removed to coerce a more strict classification. We therefore propose a novel design space.

Design Space

The unique requirements for external communication of AVs call for structured analysis to identify challenges and opportunities for future interaction design, which is currently missing.

Process

According to the approach of morphological analysis, we combined relevant values of the dimensions in a multidimensional matrix, also called “Zwicky Box” [40]. This is an established tool for ideation and design space creation (e.g., [3, 18]). This matrix contains all possible combinations of parameters relevant for a given problem. Through classification of related work, it is possible to identify promising approaches as well as a lack of solutions. In the fourth step of the analysis [40], solutions are “closely analyzed and evaluated with respect to the purposes”. This may involve dropping solutions or dimensions.

DIMENSIONS

D1 Message Type:
Instruction, Command, Advisory, Answer, Historical, and Predictive (see Buck [8])

D2 Modality:
Auditory, Visual, and Tactile/Physical

D3 Locus:
Vehicle, Personal Device, and Infrastructure (see Mahadevan et al. [25])

D4 Communication Participants:
one-to-one, one-to-many, many-to-one, and many-to-many (see Jensen and Helles [19])

To simplify the design space, we excluded dimensions such as *Technology* or *Position on Locus*. While there are various technologies employed in today's proposed concepts (displays [15], LED strips [15, 23], movement patterns [39], projections [1] auditory or tactile cues [25] as well as combinations thereof [25] and enhancement of the infrastructure [35]), this design space should not exclude upcoming technologies (e.g., aforementioned shape changing interfaces [20]).

For the *Position on Locus*, Colley et al. [9] presented a design space for external displays on cars. They proposed various example areas: bumper, grille, wheels, side mirrors, windows, license plate, on road projection, car body surfaces, and the lights. Eisma et al. [13] investigated the effect of position on crossing intention and eye-gaze using the levels *Roof*, *Windscreen*, *Grill*, *above the Wheels* and *Projection*. A generalized *Position on Locus* seems not possible nor desirable as the *Locus* is variable (Vehicle, Personal Device, and Infrastructure) and the shapes of vehicles for instance could change.

In the following, we describe the dimensions of the design space based on the SMCR model [7] and DeVito's interactive model [11]. For the actual values see the sidebar.

Dimensions and Values
We found the *1. message* and *2. channel* to be variables that are modifiable for the external communication of AVs. The first dimension therefore is **D1** *Message Type*. Most of the information currently sought from displays is of the answer kind [27]. We distinguish **D1** *Message Type* in *Implicit* and *Explicit* [17,38]. Implicit means "suggested but not communicated directly" [12]. "I'm about to start" [23] is therefore treated as an implicit message as it does not state that the pedestrian should wait. Communicating via movement is also considered to be implicit [26].

The second dimension is **D2** *Modality*. For simplicity, the variants of **D2** are not further broken down (these representation can differ in semiotic terms: *symbolic, iconic, and indexical* [28]).

The third dimension **D3** *Locus* is based on the work of Mahadevan et al. [25]. The fourth dimension **D4** *Communication Participants* is based on the work from Löcken et al. [22], who raise the question of "scalability" of the communication concepts. We propose the level *one-to-one*, *one-to-many*, *many-to-one* and *many-to-many*, known from *social media research* [19]. *One-to-one* here stands for *one* AV communicates with *one* VRU. Mahadevan et al. [24] included this aspect by simulating multiple pedestrians.

This leads to a four-dimensional design space. We present two subsets in Figure 1 and Figure 2.

			Modality					
			Auditive	Visual	Tactile/ Physical	Olfactory	Gustatory	Vestibular
Message type	Implicit	Instruction						
		Command						
		Advisory						
		Answer						
		Historical						
		Predictive						
	Explicit	Instruction						
		Command						
		Advisory						
		Answer						
		Historical						
		Predictive						

Figure 1: Matrix obtained by the morphological approach containing all parameter combinations of **D1** and **D2**. Highlighted in gray are the combinations that make technically no sense.

		Communication Participants			
		One-to-one	One-to-many	Many-to-one	Many-to-many
Locus	Vehicle				
	Device				
	Infrastructure				

Figure 2: Matrix obtained by the morphological approach containing all parameter combinations of **D3** and **D4**.

First Insights

This work provides a literature based approach to a design space for external communication concepts of AVs. Based on the actual values of the dimensions, first insights can be drawn: To our knowledge, there is no related work that investigated *answers* (e.g., when a person asks via gesture if one can pass the street) or *historical* as a message type. It is, however, not clear whether such communication is useful and therefore requires further investigation. This design space also allows researchers to classify their work. While this is out of scope for this work, already interesting questions arise per concept: Is this concept intended for a one-to-one communication? Is it viable for one-to-many or many-to-many communication (referring to *scalability* [22])? The classification of the text "Cross" concept by Mahadevan et al. [25] is (according to this design space): **D1:** *Command*; **D2:** *Visual*; **D3:** *Vehicle*; **D4:** (evaluated for) *one-to-one*.

Future Work

We will discuss the current design space with other researcher in this area and will, if necessary, make relevant adjustments. A workshop on the design space will be held with experts in the field of communication research. Current external communication concepts will be classified according to the design space. Furthermore, we want to explore the design space and implement some of the potential communication possibilities.

Acknowledgements

This work was conducted within the project 'Interaction between automated vehicles and vulnerable road users' (Intuitiver) funded by the Ministry of Science, Research and Arts of the State of Baden-Württemberg.

REFERENCES

[1] Claudia Ackermann, Matthias Beggiato, Sarah Schubert, and Josef F Krems. 2019. An experimental study to investigate design and assessment criteria: what is important for communication between pedestrians and automated vehicles? *Applied ergonomics* 75 (2019), 272–282.

[2] Michael J Auller. 1991. PICTIVE-An exploration in participatory design. (1991).

[3] Rafael Ballagas, Sarthak Ghosh, and James Landay. 2018. The design space of 3D printable interactivity. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 2 (2018), 61.

[4] Dean C Barnlund. 1970. A Transactional Model of Communication in Sereno and Mortensen eds. Foundations of Comnunication Theory. *Harper and Row* 18 (1970), 50.

[5] Pavlo Bazilinskyy, Dimitra Dodou, and JCF De Winter. 2019. Survey on eHMI concepts: The effect of text, color, and perspective. *Manuscript submitted for publication* (2019).

[6] Mercedes Benz. 2015. Der Mercedes-Benz F 015 Luxury in Motion. https://www.mercedes-benz.com/de/innovation/forschungsfahrzeug-f-015-luxury-in-motion/. (2015). [Online; accessed: 07-DECEMBER-2019].

[7] David K Berlo. 1960. The Process of Communication. New York: Holt. *Rinehart and Winston* (1960), 30.

[8] J.R. Buck. 1983. Visual displays. In *Human Factors: Understanding People-System Relationships*, Robert D Sorkin and Barry H Kantowitz (Eds.). Wiley, New York, 195–231.

[9] 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*. ACM, 146–151.

[10] Mark Colley, Marcel Walch, Jan Gugenheimer, and Enrico Rukzio. 2019. Including People with Impairments from the Start: External Communication of Autonomous Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings (AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 307–314. DOI: http://dx.doi.org/10.1145/3349263.3351521

[11] Joseph A DeVito. 2012. *The interpersonal communication book*. Pearson Higher Ed.

[12] Cambridge Dictionary. 2019. implicit. https://dictionary.cambridge.org/de/worterbuch/englisch/implicit. (2019). [Online; accessed: 05-NOVEMBER-2019].

[13] YB Eisma, S van Bergen, SM ter Brake, MTT Hensen, WJ Tempelaar, and JCF de Winter. 2019. External human-machine interfaces: The effect of display location on crossing intentions and eye movements. *Delft University of Technology* (2019).

[14] Daniel J Fagnant and Kara Kockelman. 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice* 77 (2015), 167–181.

[15] Evelyn Florentine, Mark Adam Ang, Scott Drew Pendleton, Hans Andersen, and Marcelo H. Ang Jr. 2016. Pedestrian notification methods in autonomous vehicles for multi-class mobility-on-demand service. In *Proceedings of the Fourth International Conference on Human Agent Interaction*. ACM, 387–392.

[16] James D Foley, Victor L Wallace, and Peggy Chan. 1984. The human factors of computer graphics interaction techniques. *IEEE computer Graphics and Applications* 4, 11 (1984), 13–48.

[17] Tanja Fuest, Lenja Sorokin, Hanna Bellem, and Klaus Bengler. 2017. Taxonomy of traffic situations for the interaction between automated vehicles and human road users. In *International Conference on Applied Human Factors and Ergonomics*. Springer, 708–719.

[18] Teresa Hirzle, Jan Gugenheimer, Florian Geiselhart, Andreas Bulling, and Enrico Rukzio. 2018. Towards a Symbiotic Human-Machine Depth Sensor: Exploring 3D Gaze for Object Reconstruction. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. ACM, 114–116.

[19] Klaus Bruhn Jensen and Rasmus Helles. 2017. Speaking into the system: Social media and many-to-one communication. *European Journal of Communication* 32, 1 (2017), 16–25.

[20] Matthijs Kwak, Kasper Hornbæk, Panos Markopoulos, and Miguel Bruns Alonso. 2014. The design space of shape-changing interfaces: a repertory grid study. In *Proceedings of the 2014 conference on Designing interactive systems*. ACM, 181–190.

[21] Richard Lanham. 2003. *Analyzing prose*. A&C Black.

[22] Andreas Löcken, Carmen Golling, and Andreas Riener. 2019. How Should Automated Vehicles Interact with Pedestrians?: A Comparative Analysis of Interaction Concepts in Virtual Reality. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, 262–274.

[23] Victor Malmsten Lundgren, Azra Habibovic, Jonas Andersson, Tobias Lagström, Maria Nilsson, Anna Sirkka, Johan Fagerlönn, Rikard Fredriksson, Claes Edgren, and Stas Krupenia. 2017. *Will there be new communication needs when introducing automated vehicles to the urban context?* Springer, 485–497.

[24] Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James E Young, and Ehud Sharlin. 2019. AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. ACM, 475–486.

[25] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. 2018. Communicating awareness and intent in autonomous vehicle-pedestrian interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 429.

[26] Dylan Moore, Rebecca Currano, G Ella Strack, and David Sirkin. 2019. The Case for Implicit External Human-Machine Interfaces for Autonomous Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, 295–307.

[27] University of Leicester. Year unknown. Classification of types of Information. https://www.le.ac.uk/oerresources/psychology/ergonomics/page_07.htm. (Year unknown). [Online; accessed: 05-NOVEMBER-2019].

[28] The University of Vermont. 2017. Semiotic Terminology. uvm.edu/~tstreete/semiotics_and_ads/terminology.html. (2017). [Online; accessed: 05-NOVEMBER-2019].

[29] Amir Rasouli, Iuliia Kotseruba, and John K Tsotsos. 2017. Understanding pedestrian behavior in complex traffic scenes. *IEEE Transactions on Intelligent Vehicles* 3, 1 (2017), 61–70.

[30] Amir Rasouli and John K Tsotsos. 2019. Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems* (2019).

[31] J Dan Rothwell. 2010. *In the company of others: An introduction to communication*. Oxford University Press New York.

[32] Alexandros Rouchitsas and Håkan Alm. 2019. External Human–Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Frontiers in Psychology* 10 (2019), 2757.

[33] Wilbur Schramm. 1997. *The beginnings of communication study in America: A personal memoir*. Sage.

[34] Claude E Shannon and Warren Weaver. 1949. A mathematical model of communication. *Urbana, IL: University of Illinois Press* 11 (1949).

[35] Andreas Sieß, Kathleen Hübel, Daniel Hepperle, Andreas Dronov, Christian Hufnagel, Julia Aktun, and Matthias Wölfel. 2015. Hybrid City Lighting-Improving Pedestrians' Safety through Proactive Street Lighting. In *2015 International Conference on Cyberworlds (CW)*. IEEE, 46–49.

[36] Sarah Trenholm. 2013. *Thinking Through Communication: Pearson New International Edition*. Pearson Higher Ed.

[37] Volkswagen. 2019. Studie Sedric. https://www.volkswagen-newsroom.com/de/studie-sedric-3552. (2019). [Online; accessed: 07-DECEMBER-2019].

[38] Francisco Yus. 1999. Misunderstandings and explicit/implicit communication. *Pragmatics. Quarterly Publication of the International Pragmatics Association (IPrA)* 9, 4 (1999), 487–517.

[39] Raphael Zimmermann and Reto Wettach. 2017. First step into visceral interaction with autonomous vehicles. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, 58–64.

[40] Fritz Zwicky. 1967. The morphological approach to discovery, invention, research and construction. In *New methods of thought and procedure*. Springer, 273–297.