Designing for Casual Human-Robot Collaboration in Urban Public Spaces

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Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy
2026

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2026

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Keywords

urban robots; human-robot interaction; human-robot collaboration

Abstract

Robots are evolving beyond their traditional roles in semi-controlled environments and are increasingly being deployed in dynamic public urban spaces (e.g., delivery robots). To ensure smooth deployment in these settings, robots must navigate around people and respond to unpredictable situations—circumstances in which they may experience operational difficulties and require human assistance. However, unlike robots in relatively static environments such as laboratories or domestic settings, in which robots interact with a consistent user group, urban robots encounter a diverse public, most of whom are bystanders without a pre-determined intention to interact. This fundamental difference shifts the dynamics of human–robot collaboration. Bystanders often have misaligned task objectives and are non-obligated participants in relation to urban robots, giving rise to what we term casual human–robot collaboration: forms of collaboration that emerge spontaneously during their encounters. At a broader level, urban robots are increasingly seen not just as technological applications, but as entities deeply entwined with the spatial, social, and cultural dynamics of cities. These contextual and relational shifts necessitate tailored strategies to facilitate spontaneous interactions between urban robots and bystanders.

This thesis aims to develop interaction strategies that facilitate casual collaboration between urban robots and bystanders. To achieve this, first, an online ethnography study and a field study using a design probe were conducted to identify opportunities and gain preliminary insights into how casual collaboration may emerge. Second, building on this contextual research, the thesis adopts a research-through-design approach, beginning with a design investigation through bodystorming that generates design considerations to facilitate casual human-robot collaboration. Third, these considerations inform the subsequent design concepts, which are implemented and evaluated in three empirical case studies, including both VR lab studies and in-the-wild experiments. The three studies correspond to distinct scenarios where casual human-robot collaboration emerges, as identified in the contextual research: human-robot spatial conflicts, robot-environment misalignments, and robot technological limitations. The case studies examined the effectiveness of the design concepts and their impact on people's attitudes toward urban robots. Additionally,

this thesis reports on techniques and considerations for prototyping human-robot interactions in VR.

This thesis contributes to the field of Human–Computer Interaction and Human-Robot Interaction in the following aspects: First, it identifies design opportunities and considerations for casual human-robot collaboration through contextual research. Second, the thesis presents design artefacts and reflections along the design process through the documentation of the RtD approach. Third, it provides empirical insights into how people engage with these design concepts and examines their impact on people. Fourth, it offers practical methods and considerations for prototyping and evaluating human-robot interaction in public spaces.

Glossary of Terms

Human-Computer Interaction (HCI) - "is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them." (Hewett et al., 1992)

Human-Robot Interaction (HRI) - is an interdisciplinary field that studies the interactions between humans and robots. HRI is methodologically influenced by HCI, however, has its own objectives (e.g. trust is an important criterion in HRI research).

Human-Robot Collaboration (HRC) - refers to situations where humans and robots work together toward a shared goal. Traditionally framed within industrial contexts, HRC has focused on efficiency, safety, and task performance, emphasising joint intention, shared task execution, and mutual adaptation between human and robot partners.

Urban Robot - refers to a cyber-physical system that is equipped with sensors and computing power to autonomously operate in the urban environment. Within the scope of this thesis, we only examine mobile urban ground robots, or in other words, urban robots that are not bound to a static location but capable of moving while in contact with the ground.

Prototyping - "is an activity with the purpose of creating a manifestation that, in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole." (Lim et al., 2008)

Contents

Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Name: Xinyan Yu

Date: 11th December 2025

Authorship Attribution Statement

The publications listed below have been included in this thesis as separate chapters, following the University of Sydney's policies for a thesis including publications[1]. Each publication makes a research contribution in its own right and comes with its individual subsections of related work, methodology, findings, discussion and conclusions. Below, the authorship attribution statement is included for each respective publication. Affiliations are based on the positions the co-authors held at the time of writing the papers.

In order to capture the contribution from myself as well as my co-authors, I chose to use the first person plural throughout all chapters of this thesis. However, the Discussion chapter will be presented in the first person singular to emphasise my personal reflections and learnings as a PhD candidate.

Chapter 3

Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Martin Tomitsch (2024). Understanding the interaction between delivery robots and other road and sidewalk users: A study of user-generated online videos. In *ACM Transactions on Human-Robot Interaction (THRI)*.

This chapter was co-authored as a journal article with Dr Marius Hoggenmüller, Dr Tram Thi Minh Tran, Dr Yiyuan Wang from the Design Lab, Sydney School of Architecture, Design and Planning, the University of Sydney; and Professor Martin Tomitsch from the Transdisciplinary School at the University of Technology Sydney.

This chapter presents an online ethnography that investigates real-world encounters between people and delivery robots through user-generated videos and comments on TikTok. I developed the study protocol, collected and processed the data, conducted the analysis, and drafted the paper. The data screening and coding were conducted collaboratively with Dr. Tram Thi Minh Tran and Dr. Yiyuan Wang. My PhD supervisors Dr. Marius Hoggenmüller and Professor Martin Tomitsch contributed to

[1] `https://www.sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`, accessed November 2025

the study planning, the development of the coding scheme, and were involved in the review and editing of this paper.

The paper was published as an article in the ACM Transactions on Human-Robot Interaction (Volume 13, Issue 4, Article 59, December 2024).

Chapter 4

Xinyan Yu, Tram Thi Minh Tran, Yiyuan Wang, Kristina Mah, Yidan Cao, Stine S Johansen, Wafa Johal, Maria Luce Lupetti, Megan Rose, Markus Rittenbruch, Rodney G Zsolczay, Marius Hoggenmüller (2024). Out of Place Robot in the Wild: Envisioning Urban Robot Contextual Adaptability Challenges Through a Design Probe. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHIEA '24).

This chapter was co-authored as a conference late-breaking work paper that reports on results from a workshop that I led at OzCHI 2023. The paper was co-authored with Dr. Marius Hoggenmüller, Dr. Tram Thi Minh Tran, and Dr. Yiyuan Wang from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney, who were co-organisers of the workshop; Dr. Kristina Mah and Yidan Cao from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney; Dr Stine S. Johansen from the Australian Cobotics Centre, Queensland University of Technology; Associate Professor Wafa Johal from the School of Computing and Information Systems, The University of Melbourne; Associate Professor Maria Luce Lupetti from the Faculty of Industrial Design Engineering, TU Delft; Dr. Megan Rose from the ARC Centre of Excellence for Automated Decision-Making and Society and the Vitalities Lab, University of New South Wales; Professor Markus Rittenbruch from the QUT Design Lab, Queensland University of Technology; and Rodney G. Zsolczay from Queensland University of Technology, who participated in the workshop.

I developed the design probe used in the workshop and related activities, which Dr. Marius Hoggenmüller, Dr. Tram Thi Minh Tran, and Dr. Yiyuan Wang, as workshop co-organisers, also contributed to. I conducted the data analysis and drafted the paper, with additional input on both the analysis and writing from my supervisor, Dr. Marius Hoggenmüller. All co-authors were involved in the review and editing of this paper.

This chapter was presented as a poster at the 2024 ACM Conference on Human Factors in Computing Systems (CHI) in Honolulu, USA, and was published in the proceedings of the conference, available in the ACM Digital Library.

Chapter 5

Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2023). Your Way Or My Way: Improving Human-Robot Co-Navigation Through Robot Intent and Pedestrian Prediction Visualisations. In *Proceedings of the ACM CHI Conference on Human-Robot Interaction (HRI '23)*

This chapter was co-authored as a conference paper with my supervisors Dr. Marius Hoggenmüller and Professor Martin Tomitsch from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney.

This study originated as part of my Master's research capstone, during which I conceptualised the study, developed the design concept of pedestrian path prediction visualisation, VR simulation, and study design in collaboration with my supervisors Dr. Marius Hoggenmüller. The data collection was conducted by me partly during my Master's and was subsequently extended during my PhD, during which I also conducted the data analysis and manuscript writing. As this was my first piece of academic writing, my supervisors Marius and Martin contributed significantly to refining and editing the manuscript, particularly the Related Work and Discussion sections. Marius also contributed to creating figures that visualise the quantitative results.

This chapter was presented at the 2023 ACM/IEEE International Conference on Human-Robot Interaction (HRI), held in Stockholm, Sweden, and was published in the proceedings of the conference, available in the ACM Digital Library.

Chapter 6

Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch. (2024). From Agent Autonomy to Casual Collaboration: A Design Investigation on Help-Seeking Urban Robots. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems. (CHI '24)*

This chapter was co-authored as a conference paper with my supervisors Dr. Marius Hoggenmüller and Professor Martin Tomitsch from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney.

This study includes a series of focus group sessions employing bodystorming methods to investigate how delivery robots should seek help from passersby. I developed the bodystorming activity, while my supervisor Dr. Marius Hoggenmüller contributed significantly to refining the study prompts and procedure. I was responsible for conducting the focus groups and leading the data analysis, with additional input from my supervisors Marius and Martin throughout the analysis and synthesis of findings. During the writing process, I drafted the manuscript, with Marius contributing substantially to refining the framing of the paper, and Martin Tomitsch providing significant input to strengthen the Discussion section.

This chapter was presented at the 2024 ACM Conference on Human Factors in Computing Systems (CHI) in Honolulu, USA, and was published in the proceedings of the conference, available in the ACM Digital Library.

Chapter 7

Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch (2024). Encouraging bystander assistance for urban robots: Introducing playful robot help-seeking as a strategy. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24)*.

This chapter was co-authored as a conference paper with my supervisors Dr. Marius Hoggenmüller and Professor Martin Tomitsch from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney.

This study presents the design process and VR-based evaluation of game-inspired robot help-seeking strategies. I developed the design concepts with input from both my supervisors, Marius and Martin, whose feedback helped to refine the design concepts. I designed the study and developed the VR simulation, and was responsible for conducting the study. The data analysis was led by me, with input from both my supervisors in synthesising the findings. I wrote the majority of the manuscript, with Marius contributing to the Related Work section, particularly the section on playful HRI. Both supervisors contributed to reviewing and editing the paper.

This chapter was presented at the 2024 ACM Conference on Designing Interactive Systems (DIS) in Copenhagen, Denmark, and was published in the conference proceedings, available in the ACM Digital Library.

Chapter 8

Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Martin Tomitsch (2025). Feel the Presence: The Effects of Haptic Sensation on VR-Based Human-Robot Interaction. In *Proceedings of the 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN '25)*.

This chapter was co-authored as a conference paper with Dr. Marius Hoggenmüller and Dr. Tram Thi Minh Tran from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney, and Professor Martin Tomitsch from the Transdisciplinary School, University of Technology Sydney.

This study was a follow-up to the work presented in Chapter 7, replicating the same study protocol but using a different VR setup that enabled haptic interactions. Through this comparison, the study provides insights into how the inclusion of haptic feedback influences assessment in VR-based HRI studies. I conceptualised the study in discussion with my supervisors Marius and Martin, and was responsible for developing the VR simulation. I conducted the study, analysed the data, and drafted the manuscript. Both my supervisors, Marius and Martin, as well as Dr. Tram Thi Minh Tran, who brought in expertise in VR, were involved in reviewing and editing the paper.

This chapter was presented at the 2025 IEEE International Conference on Robot and Human Interactive Communication (Ro-Man) in Eindhoven, Netherlands, and was published in the conference proceedings, available in the IEEE Digital Library.

Chapter 9

Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Qiuming Zhang, Martin Tomitsch. (2025). Peek into the 'White-Box': A Field Study on Bystander Engagement with Urban Robot Uncertainty. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*.

This chapter was co-authored as a conference paper with Dr. Marius Hoggenmüller, Dr. Tram Thi Minh Tran, Dr. Yiyuan Wang, Qiuming Zhang from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney, and Professor Martin Tomitsch from the Transdisciplinary School, University of Technology Sydney.

This study is a Wizard-of-Oz field study of a speculative design concept "Peephole", which investigates how bystanders can be invited to assist urban robots when they encounter uncertainties. The study was conceptualised by me in discussion with my supervisors, Dr. Marius Hoggenmüller and Professor Martin Tomitsch. The "Peephole" concept was initially proposed by me, with Marius providing valuable guidance in strengthening its theoretical grounding and refining the design concept. I conducted the field study with Dr. Tram Thi Minh Tran, Dr. Yiyuan Wang, and Qiuming Zhang supporting as the wizard. I analysed the data with input from my supervisors and drafted the manuscript. Marius, Tram and Martin were involved in reviewing and editing the paper.

This chapter was presented at the 2025 ACM Conference on Human Factors in Computing Systems (CHI) in Yokohama, Japan, and was published in the proceedings of the conference, available in the ACM Digital Library.

Generative AI Attribution Statement

During the preparation of this thesis, ChatGPT was used for the purposes of text enhancement. This generative AI tool was employed primarily for spelling corrections and for seeking suggestions related to minor sentence restructuring and clarity improvements, serving as a substitute for a traditional proofreading process. All AI-assisted suggestions were manually reviewed and edited by the author to avoid possible errors, inaccuracies, and bias.

The author takes full responsibility for the submitted thesis, confirms the work is their own, and has used generative AI in accordance with University guidelines and policies.

List of Publications

The following publications were achieved during my PhD candidature. Publications marked with an asterisk are included as chapters in this thesis.

Conference Papers

* Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2023). Your Way Or My Way: Improving Human-Robot Co-Navigation Through Robot Intent and Pedestrian Prediction Visualisations. In *Proceedings of the ACM CHI Conference on Human-Robot Interaction (HRI '23)*.

* Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2024). From Agent Autonomy to Casual Collaboration: A Design Investigation on Help-Seeking Urban Robots. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*.

* Xinyan Yu, Tram Thi Minh Tran, Yiyuan Wang, Kristina Mah, Yidan Cao, Stine S Johansen, Wafa Johal, Maria Luce Lupetti, Megan Rose, Markus Rittenbruch, Rodney G Zsolczay, Marius Hoggenmüller (2024). Out of Place Robot in the Wild: Envisioning Urban Robot Contextual Adaptability Challenges Through a Design Probe. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHIEA '24)*.

* Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch (2024). Encouraging bystander assistance for urban robots: Introducing playful robot help-seeking as a strategy. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24)*.

* Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Martin Tomitsch (2025). Feel the Presence: The Effects of Haptic Sensation on VR-Based Human-Robot Interaction. In *Proceedings of the 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN '25)*.

* Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Qiuming Zhang, Martin Tomitsch. (2025). Peek into the 'White-Box': A Field Study on Bystander Engagement with Urban Robot Uncertainty. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*.

Tran, Tram Thi Minh, Xinyan Yu, Marius Hoggenmüller, Callum Parker, Paul Schmitt, Julie Stephany Berrio Perez, Stewart Worrall, and Martin Tomitsch (2025). Animal Interaction with Autonomous Mobility Systems: Designing for Multi-Species Coexistence. In *Proceedings of the 17th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI '25)*.

Luo, Yue, Xinyan Yu, Tram Thi Minh Tran, and Marius Hoggenmüller (2025). Uncertainty on Display: The Effects of Communicating Confidence Cues in Autonomous Vehicle-Pedestrian Interactions. In *Proceedings of the 17th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI '25)*.

Tram Thi Minh Tran, Xinyan Yu, Yiyuan Wang, Callum Parker, Martin Tomitsch (2024). Mapping Pedestrian-to-Driver Gestures: Implications for Autonomous Vehicle Bidirectional Interaction. In *Adjunct Proceedings of the 16th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI '24)*.

Yiyuan Wang, Xinyan Yu, Tram Thi Minh Tran, Martin Tomitsch (2024). The Role of Emotional Expressions by Autonomous Agents in Road-Sharing: Using Scenario Prompts in Online Video and Virtual Reality Studies. In *Proceedings of the 35th Australian Computer-Human Interaction Conference (OzCHI '24)*.

Qiuming Zhang, Xinyan Yu, Joel Fredericks, Marius Hoggenmueller (2024). Rethinking Urban Safety: Exploring The Design of Safety Robots from Women's Perspectives. In *Proceedings of the 35th Australian Computer-Human Interaction Conference (OzCHI '24)*.

Yiyuan Wang, Xinyan Yu, Martin Tomitsch (2023). Designing Emotional Expressions of Autonomous Vehicles for Communication with Pedestrians in Urban Shared Spaces: Use Cases, Modalities, and Considerations. In *Proceedings of the 35th Australian Computer-Human Interaction Conference (OzCHI '23)*.

Journal Articles

* Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Martin Tomitsch (2024). Understanding the interaction between delivery robots and other road and sidewalk users: A study of user-generated online videos. In *ACM Transactions on Human-Robot Interaction (THRI)*.

Tram Thi Minh Tran, Callum Parker, Xinyan Yu, Debargha Dey, Marieke Martens, Pavlo Bazilinskyy, Martin Tomitsch (2024). Evaluating Autonomous Vehicle External Communication Using a Multi-Pedestrian VR Simulator. In *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT)*.

Martin Tomitsch, Joel Fredericks, Marius Hoggenmüller, Alexandra Crosby, Adrian Wong, Xinyan Yu, Weidong Huang (2025). AI-Supported Participatory Workshops: Middle-Out Engagement for Crisis Events. In *Urban Planning*.

Workshop Organisation

Xinyan Yu, Julie Stephany Berrio Perez, Marius Hoggenmüller, Martin Tomitsch, Tram Thi Minh Tran, Stewart Worrall, and Wendy Ju (2025). The UnScripted Trip: Fostering Policy Discussion on Future Human–Vehicle Collaboration in Autonomous Driving Through Design-Oriented Methods. In *Adjunct Proceedings of the 17th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI '25)*.

Xinyan Yu, Yiyuan Wang, Tram Thi Minh Tran, Yi Zhao, Julie Stephany Berrio Perez, Marius Hoggenmüller, Justine Humphry, Lian Loke, Lynn Masuda, Callum Parker, Martin Tomitsch, Stewart Worrall (2023). Robots in the Wild: Contextually-Adaptive Human-Robot Interactions in Urban Public Environments. Accepted as a workshop to the *35nd Australian Conference on Human-Computer Interaction (OzCHI '23)*.

Acknowledgements

First, I would like to acknowledge my lead supervisor, Dr Marius Hoggenmüller, who guided me into the area of HRI design research four years ago, at a time when I had just arrived in this country and was still finding my place and passion. I feel incredibly lucky to have a supervisor whose research interests and working style align so well with mine, and whose intelligence and dedication to research have deeply influenced me. Thank you for being consistently encouraging, considerate and generous in your support; I would not have made it through this journey so smoothly without your support, especially in the early stage when I was still figuring out what design research really means. Thank you also for the countless thoughtful comments and meetings that helped me learn how to think, write, and grow as a researcher.

I am immensely thankful for the guidance of Professor Martin Tomitsch, and for introducing me to the broader Mobility and Robotics research group. It has been incredible to have the opportunity to work with you, especially knowing that seeing your talks from videos was one of the reasons I came to Australia to join the M.IDEA program, which later opened the path for my journey as a researcher in HCI. Thank you for always making time for our PhD meetings despite your busy schedule; it not only played a significant role in shaping my research but also meant a lot to me and made me feel truly supported. Your way of thinking, working, and caring for people has always inspired me, both as a researcher and as a person, and has become something I truly aspire toward.

I feel really lucky to have had the chance to work among the amazing people in the Australian Centre for Field Robotics and Urban Interfaces Lab, who have greatly enriched my PhD journey and collaboration experiences. Thank you, Dr Stewart Worrall, Dr Stephany Berrio Pérez, and Dr Mao Shan, for your invaluable input at different stages of this project and for sharing your expertise as robotics researchers. I truly enjoyed our bi-weekly group meetings, where we explored and discussed research ideas from an interdisciplinary perspective. Those conversations broadened my thinking, and I am truly grateful for the opportunities from the group to get involved in work on autonomous vehicles that extended beyond my own PhD project.

I would also like to express my gratitude to Professor Andrew Vande Moere, who hosted me as a visiting researcher at KU Leuven and introduced me to the wonderful research area of robotic furniture and public displays. Thank you, Dr Alex Binh Vinh Duc Nguyen, for helping me build the bench and for being there during the field study at the library.

When I started my PhD, I received a great deal of support from the senior PhD students at the time, Dr Tram Thi Minh Tran and Dr Yiyuan Wang. Thank you, Tram, for your care and generosity. I learned so much from the way you organise things and from your direct, sharp way of thinking. And thank you also for introducing me to ACO. Their music has become the background soundtrack of my writing. Thank you, Yiyuan, for all the discussions and reassurance during the early stages of my research, when I had so many hesitations and uncertainties.

I would also like to thank all the amazing PhD students in Mezz. It is sad that we lost the space by the time I submitted my thesis, but I am grateful that we still carry so many good memories from it. Thank you, Natalia Gulbransen-Diaz and Ajit Pillai, for welcoming me to the place with a piñata — it is still sitting on my desk as I write this line. Thank you, Yidan Cao, Yizhao, Dylan Chen, Tim Cook, Kristina Mah, Brittany Klaassens, Jo Martin, Yifan Kong, Russian Wu, Mindy, and Xuefei Li, for all the conversations, laughter, and companionship throughout this journey.

At last, I would like to thank all my family. I am deeply grateful to my parents, who, despite carrying so many worries, still supported me in studying in another country during COVID and have given me unconditional love throughout this journey. Grandma and Grandpa, you have influenced me as a person in ways I did not realise until much later. Your love has shaped who I am, and your dumplings have always been the taste of home. Last but not least, thank you to my partner, Dr Xin Lu, for being the opposite that balances the anxious and impatient parts of me, but at the sametime, being so similar in other ways that make me feel deeply understood.

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This research was funded by the Australian Research Council through the ARC Discovery Project DP220102019 Shared-Space Interactions Between People and Autonomous Vehicles.

Part I

Background

Introduction | 1

1.1 Background & Motivation

1.1.1 Robots in Urban Spaces

Robots have long been confined to laboratories, factory floors, or imagined worlds of futuristic media. Now, however, they are increasingly making their presence in public urban spaces—robotaxis transporting passengers through city streets (Block et al., 2023), delivery robots sharing footpaths with pedestrians (Pelikan et al., 2024), service robots assisting people in airports and malls (Chen et al., 2017; Hwang et al., 2023), and security robots patrolling public areas (Ye et al., 2024).

Often, these robots are designed to provide services that benefit their intended users, for example, delivering parcels to recipients or assisting travellers with navigation. However, their operation in public spaces inevitably affects others: people who were not intended to engage with these robots but nonetheless encounter them incidentally in their everyday routines (Rosenthal-von der Pütten et al., 2020; Dobrosovestnova et al., 2025). At a fundamental level, urban robots share physical space with city dwellers and sometimes operate in close proximity to them, making safe navigation an essential requirement (Yasuda et al., 2020). At the same time, as part of the social fabric of urban spaces, robots are expected to align with social norms and etiquette (Lynn, 2020). This can be achieved through engineering solutions such as socially aware navigation planning (Ferrer et al., 2013a; Li et al., 2020) or interfaces that support social interactions during encounters with people (Wang et al., 2023; Weiss et al., 2015).

At a macro level, urban robots are increasingly viewed not merely as technological applications deployed within urban spaces, but as entities deeply entangled in the spatial, social, cultural dynamics of cities. For example, Nagenborg (2020) point out that urban robot integration must preserve and enhance *"cityness"*, suggesting that robots should contribute positively to the overall quality of urban life. Pelikan et al. (2025) integrates insights from HRI with urban sociology, particularly drawing on the work of William H. Whyte and his *Street Life Project* (Whyte et al., 1980), to propose a framework for public robot design that moves beyond viewing robots as mere physical entities in space. The framework foregrounds the importance of designing robots that engage with various aspects of placemaking, considering how robots align with a place's identity and culture, and how they respond to everyday and situational practices unfolding in that space.

1.1.2 The Extended Landscape of Human-Robot Collaboration

Over the past decades, research in human–robot collaboration (HRC) has studied how humans and robots can collaborate together across a variety of tasks and settings, ranging from industrial manufacturing (Matheson et al., 2019) and healthcare (Baratta et al., 2023) to creative domains (Zhao et al., 2025). Within these collaborations, humans can assume various roles, such as supervisors, operators, or teammates, generally sharing joint task goals and closely cooperating with the robot (Kolbeinsson et al., 2019).

Bystanders, in contrast—people who do not share the same goals with the robot or have any pre-existing intention to interact with it—occupy the least engaged end of the spectrum of human roles in HRI (Onnasch and Roesler, 2021; Scholtz, 2003), and have traditionally been excluded from considerations of collaboration. Earlier frameworks often characterised bystanders as individuals limited to passive spatial coexistence, without involvement in any active interaction with robots (Scholtz, 2003). As a result, avoidance (e.g., preventing unintended collisions between robots and bystanders) has long been the primary design consideration for this group (Onnasch and Roesler, 2021).

However, the increasing deployment of robots in public spaces has led to more frequent, incidental encounters between bystanders and robots, broadening the scope of possible interactions. In recent years, studies in the field have observed that bystanders exhibit a wide range of behaviours during such encounters, including exploratory, obstructive, aggressive, or supportive responses (Salvini et al., 2010; Dobrosovestnova et al., 2022; Pelikan et al., 2024; Cheon and Shin, 2025; Weinberg et al., 2023). Furthermore, collaborations in more peripheral or situational forms can emerge during these encounters. For instance, passersby often subtly adjust their trajectories in response to a robot's movement on a sidewalk, engaging in a form of contingent and situational coordination (Reeves et al., 2025; Pelikan et al., 2024). In situations where robots become stuck, bystanders have been observed actively assisting (e.g, by making space for them (Pelikan et al., 2024) or pushing them out of snow-covered paths (Dobrosovestnova et al., 2022)), demonstrating spontaneous collaboration that arises from shared spatial and situational awareness.

Recognising this, HRI researchers have recently begun to advocate for a more nuanced understanding of HRC, extending collaboration beyond tightly coupled, goal-aligned tasks to include loosely coordinated and emergent forms of collaboration (Reeves et al., 2025). Aligning with this shift and in response to the increasing encounters between urban robots and bystanders, this thesis investigates the extended landscape of HRC from a design perspective, with the aim of exploring how to support what I refer to as *casual human-robot collaboration* between bystanders and urban robots.

1.1.3 Motivation

The increasing presence of robots in public spaces means that their interactions with people are no longer confined to intended users but frequently involve bystanders. While much existing HRI research has focused on optimising robot performance for goal-directed tasks with known users, there remains a significant gap in understanding and designing for the spontaneous, informal, and often fleeting encounters that arise with bystanders in complex urban environments.

At the same time, social acceptance and public trust, critical factors for the integration of robots into urban environments (Nagenborg, 2020), have predominantly been examined in the context of structured, goal-directed interactions with intended users. This leaves open the question of how trust and acceptance may be shaped during incidental encounters with bystanders. The design of casual human–robot collaborations holds important implications not only for the safety and efficiency of robot operation, but also for fostering acceptance and trust, thereby contributing to the smooth integration of robots into urban public spaces.

1.2 Research Aim and Questions

The aim of this research is to **investigate how to design for casual human-robot collaboration**, thereby supporting their integration into everyday urban environments.

Unlike traditional human–robot collaboration, which often centres on well-defined tasks and explicit goals, casual collaboration emerges spontaneously from incidental encounters in public spaces. These interactions are not pre-determined, but arise spontaneously through everyday urban routines. Therefore, the first essential step of this research is to understand the real-world situations in which such casual collaborations could occur (Chapters 3, 4). To set the contextual foundation for the later design investigation in this thesis, and to uncover opportunities for casual collaboration between urban robots and bystanders, we ask the following question:

RQ1. Understanding: In what situations does casual collaboration between urban robots and bystanders unfold? What design opportunities are emerging from these situations?

Despite the existence of numerous human–robot collaboration frameworks and interaction design concepts (Matheson et al., 2019; Baratta et al., 2023; Cila, 2022), these approaches largely overlook the dynamic nature of incidental encounters and the distinct role of bystanders, who have no pre-existing relationship with the robot. This unique context fundamentally shifts the character of human-robot collaborations (Reeves et al., 2025). Therefore, design research tailored to this new context is needed in order to understand what interaction strategies are suitable for facilitating such casual collaborations. The main part of this thesis addresses this need through design workshops and focus groups that inform novel design concepts for casual collaboration (Chapters 6 and 7), and through empirical studies that validate the effectiveness of these concepts in real or simulated urban contexts (Chapters 5, 7, 8, and 9). Through these studies, this research seeks to answer the following question:

RQ2. Designing: How can we design interactions that facilitate casual collaboration between bystanders and urban robots?

Finally, since the integration of urban robots into city spaces is not only a matter of technological implementation, but is also deeply entangled in the social dynamics of urban life, it is important not only to evaluate the effectiveness of design concepts, but also to understand how such collaboration shapes people's perceptions and attitudes of robots in everyday urban contexts. Thus, this research seeks to answer the following question:

RQ3. Evaluating: How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?

1.3 Methodology

The methodology for this research is two-staged, beginning with contextual research grounded in real-world encounters with urban robots, which informs the subsequent design investigation conducted through a Research through Design (RtD) approach. Figure 1.1 presents a structured progression of the research, based on the selected methodology.

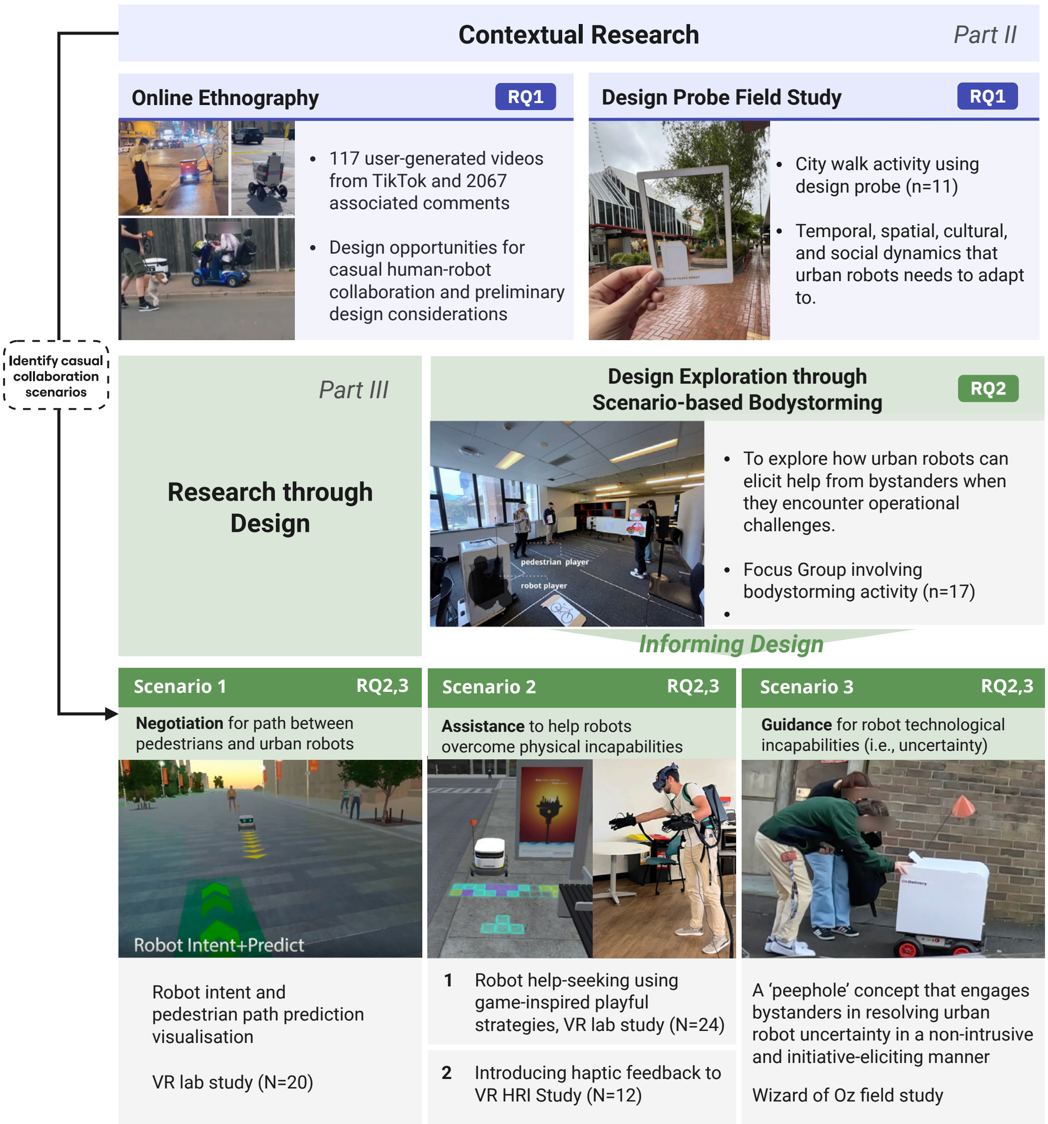

Fig. 1.1.: Overview of the primary studies comprising this thesis, their methods, and the respective research questions they addressed.

1.3.1 Contextual Research

Robots in urban public spaces are not only physical entities occupying urban environments, they are also intertwined with the multi-faceted nature of urban life, shaping and being shaped by everyday social dynamics. Ethnographic methods are particularly well suited for investigating the complexity of urban contexts, providing deep insights into everyday practices, tacit social rules, and situated meanings (Jaffe and De Koning, 2022). In HCI and design, ethnographic method has evolved from a peripheral approach to a central methodology for uncovering how people interact with technologies in real-world contexts, thereby sensitising designers to the social realities and constraints that should inform and inspire new technology design (Crabtree et al., 2012).

In this research, two ethnographically informed studies were conducted to establish a contextual understanding of the integration of robots into everyday urban life. The first study (Chapter 3) used online ethnography (Postill and Pink, 2012; Tomitsch et al., 2018) to examine social media content to identify situations where casual human–robot collaboration can emerge between bystanders and robots, which then informed the scenarios and design for the subsequent design investigations (Chapters 5, 7, 8, and 9). The second study (Chapter 4) situated participants in real urban environments through a city walk activity and prompted them to reflect on the imaginative presence of urban robots using a design probe (Gaver et al., 1999). The social, temporal, and spatial complexities of everyday urban life in relation to robot integration that surfaced through this contextual research further guided the subsequent design investigations.

1.3.2 Design Investigation

In recent years, research with a strong design orientation, also referred to as *designerly HRI* (Lupetti et al., 2021), has become increasingly prominent within the field. This line of research often generates knowledge that extends beyond technical implementation and traditional user studies, embracing design as a mode of inquiry in its own right. A central methodology in *designerly HRI* is Research through Design (RtD), in which design is not merely about problem-solving, but serves as a means of generating new knowledge through the methods, practices, and processes inherent to design practice(Zimmerman et al., 2007). This research is situated within the scope of *designerly HRI*, with RtD adopted as the overarching methodological approach.

The aim of the research is not just to solve a pre-defined problem, but to address the complex, open-ended challenge of integrating urban robots into city life, where dynamic contexts and diverse perspectives preclude a single "right" solution. This is achieved through an iterative exploration and reframing of the complex, situated, and emergent nature of casual collaboration between bystanders and urban robots in public spaces. The themes surfaced through this process, for example, the notion of playfulness that emerged in the early stages of design exploration (Chapter 6), have continued to evolve across subsequent empirical studies (Chapters 5, 7, 8, and 9), reflecting how design and understanding around it are reshaped through ongoing inquiry. This process aligns with the nature of RtD, with its emphasis on knowledge generation rather than solely on solution derivation. The reflective approach contributes both to producing empirically validated design recommendations to facilitate such collaboration (RQ2) and to deepening our understanding of how such collaboration is perceived, enacted, and interpreted by bystanders (RQ3).

1.3.3 Data Collection and Analysis Methods

This section provides a high-level overview of the mixed-methods approach used for data collection and analysis, while detailed procedures are presented in the individual chapters reporting the empirical studies (Chapter 6, 5, 7, 8, 9). The mixed-methods approach combines qualitative and quantitative methods to offer a more comprehensive understanding of the phenomenon (Creswell, 1999), with qualitative findings revealing contextual nuances, and quantitative analysis providing broader validation and generalisability of emergent trends.

Design Probe

The design probe method, initially introduced in (Gaver et al., 1999), utilises a range of materials to facilitate the documentation and reflections of people's daily activities. This approach has been widely adopted in design research as it offers a relatively unobtrusive and lightweight method for gaining insights into how technology can integrate into, or sometimes clash with, specific environments. Therefore, I employed this method and developed a design probe for people to carry with them, facilitating them to envision the robot's presence. The design probe study consisted of two parts: (1) distributing the design probe among the workshop organising team and recording their responses through an online brainstorming board, and (2) conducting a *City*

Walk activity using the same probe in the central area of Wellington, New Zealand, during an academic conference workshop.

The data collection methods for the design probe study include *entries consisting of photographs and written descriptions* of imaginative scenarios submitted by participants.

Focus Groups

As part of the design process for the studies presented in Chapter 5 and Chapter 6, we conducted focus groups with expert participants spanning diverse academic and professional backgrounds, including HCI, HRI, robotics engineering, and interaction design. A focus group is a qualitative research method involving a moderated discussion among a group of individuals centred on a specific topic (Krueger, 2014). It is commonly used in HCI to inform design decisions by eliciting rich insights from diverse perspectives (Lazar et al., 2017). The focus group in Chapter 5 followed a moderated group discussion format, while the session in Chapter 6 incorporated role-play and bodystorming activities to elicit situated understandings and empathy toward the design scenario. The data collection methods used in these studies included: (1) *video and audio recordings* to document activities and discussions during the sessions; (2) *observation notes* taken during the activities to support subsequent video analysis; and (3) *notes and sketches* created by participants.

Lab Studies

In this thesis, three VR lab studies were conducted (in Chapter 5, 7, and 8) to assess design concepts and enable a structured comparison of different interaction approaches and their impacts on people's attitudes toward robots. Lab studies are controlled experiments conducted in structured settings to investigate specific phenomena or test hypotheses. They are well-suited for focused evaluation and offer a high degree of experimental control (Lazar et al., 2017). At the same time, advances in VR technologies have enabled the simulation of situated interactions with design artefacts with high ecological validity, making it a promising method for investigating interactions in context (Hoggenmüller et al., 2021b; Mäkelä et al., 2020).

The data collection methods for these studies include: (1) *questionnaires* to collect subjective data reflecting participants' experiences; (2) *semi-structured interviews* to gather detailed insights into participant interactions with urban robots; (3) *video* *recordings of VR sessions and observational notes* to capture participant behaviours during the studies.

Field Study

Studying human–robot interaction in the field is essential for capturing the situated, emergent qualities of interaction that are shaped by real-world contexts (Sabanovic et al., 2006). In this thesis, a field study was conducted as part of the evaluation of design concepts (Chapter 9), in which a robot prototype was deployed in a real-world public space and passersby's unguided interactions with it were observed. The data collection methods for the field study include: (1) *video-recordings* capturing the deployment area to analyse people's interactions with the robot; (2) *observation notes* taken by the research team; (3) *audio-recordings of semi-structured interviews* conducted with passersby after observing or interacting with the robot.

Data Analysis

The audio-recorded semi-structured interviews as part of the qualitative data collection were transcribed using AI transcription services, including *Dovetail* [1] and *Descript* [2]. The transcripts were subsequently reviewed and corrected by the interviewer who conducted the sessions. The interview transcripts, along with additional qualitative data (e.g., observation notes, focus group notes), were then analysed using the thematic analysis approach (Braun and Clarke, 2006).

Video recordings were examined to identify notable interaction incidents. These were documented as textual descriptions, supplemented by screenshots extracted from the videos to provide visual context.

Quantitative data collected through questionnaires were analysed through a multi-step process, including data cleaning, data transformation, exploratory data analysis, descriptive statistics, and inferential analysis.

1.4 Significance and Contributions

The integration of urban robots into city spaces promises a range of benefits across multiple dimensions. Delivery robots can enhance last-mile delivery efficiency while

[1] https://dovetail.com/
[2] https://www.descript.com/transcription

reducing energy consumption and emissions (Figliozzi, 2020; Marks, 2019); security robots may contribute to safer urban environments (Ye et al., 2024); and robots serving as "street entertainers" can add vibrancy and new forms of engagement to public spaces (Hoggenmueller et al., 2020b; Lee and Jung, 2020). Realising these benefits, however, depends not only on technological advancements that enable robots to operate efficiently, but also on public acceptance, given their deep entanglement in the spatial, social, and broader societal dynamics of cities (Nagenborg, 2020; Pelikan et al., 2025). Recent policy agendas, such as Australia's *National Robotics Strategy* (Australian Department of Industry, Science and Resources, 2024) and the *EU Artificial Intelligence Act* (EU, 2024), underscore the timeliness of research on integrating robots into everyday environments by emphasising the importance of their trustworthy and socially beneficial deployment.

This thesis contributes to this agenda by investigating the casual collaborations that emerge in incidental encounters between people and urban robots. Facilitating such collaboration in everyday situations is crucial not only for ensuring the smooth and unobtrusive nature of these encounters, but also for fostering positive relationships between humans and robots. This, in turn, holds the potential to enhance public acceptance and support the integration of robots into urban life.

This doctoral research offers the following contributions.

Artefact Contributions: This research produces a series of design artefacts through the RtD methodology, including novel interface concepts and prototypes to facilitate casual collaboration between urban robots and bystanders, as well as documentation of the design processes.

Empirical Contributions: The research provides empirically validated design recommendations and implications about casual collaboration between urban robots and bystanders. These insights are expected to have a direct impact on informing future urban robot design, thus resulting in the seamless integration of robots into everyday urban environments.

Methodological Contributions: The research provides practical methods and considerations on prototyping human-robot interactions in VR, advancing the knowledge on both the development of VR-based HRI prototypes and the evaluation of human–robot interactions in VR.

Conceptual Contributions: This research offers a conceptualisation of casual human–robot collaboration by articulating how human–robot–environment entanglements give rise to different forms of collaboration in urban public spaces and demonstrating . It further shows how design can reconfigure these situations: from spatial conflicts to shared negotiation, from misalignments to co-engagement, and from isolated failure to distributed autonomy.

1.5 Thesis Scope

This thesis focuses on a specific subcategory of human–robot collaboration: the collaborations that occur between urban robots and bystanders. The term *urban robots* can encompass a wide range of cyber-physical systems equipped with sensors and computing power to operate autonomously in urban environments, including platforms such as aerial drones. This research concentrates exclusively on ground-based mobile robots, as these robots typically share public spaces, such as roads and sidewalks, with humans while executing their primary functions. This results in a higher frequency and greater diversity of spontaneous encounters with bystanders. Among the various functional types and morphologies that urban robots could take, this investigation centres around non-humanoid robots (Fong et al., 2003), robots that are not modelled on human (anthropomorphic) or animal (zoomorphic) forms, but are typically designed for function and therefore having purely utilitarian appearances. Specifically, this research focuses on cubic, box-shaped robots that resemble contemporary delivery robots.

In terms of human involvement, the research exclusively focuses on bystanders: individuals in public spaces who encounter the robot without being designated users or having any pre-existing relationship with it.

1.6 Thesis Structure

The core chapters consist of academic publications in accordance with the University of Sydney's regulations for a PhD thesis with publications.[3] The thesis consists of five peer-reviewed conference papers, one journal article, and one conference late-breaking work that were written and published during the candidature.

Each publication makes an original research contribution and consists of its own subsections, including related work, methodology, findings, discussion, and conclusions. To maintain a coherent thesis narrative, each publication is preceded by a preamble and is not arranged in chronological order, but in a sequence that best conveys the overarching research trajectory.

This thesis consists of ten chapters that are arranged in four parts, as outlined below.

[3] https://www.sydney.edu.au/research/graduate-research/current-students/thesis-and-examination.html, last accessed 27th November 2025.

Part I - Introduction

Chapter 1: This thesis begins by introducing the background of urban robots, followed by the motivation and research aims, along with the research questions that guide the investigation. It then outlines the methodology adopted and highlights the contributions to the field of HCI and HRI.

Chapter 2: This chapter brings together three strands of literature that inform the theoretical and contextual grounding of this thesis, clarifying its stance on human–robot collaboration and setting the stage for the following investigations.

Part II - Contextual Research

This part presents the contextual research of the thesis, aiming to establish an understanding of the current development of urban robots in real-world public space settings. It consists of an online ethnography study that analyses user-generated videos from social media that capture casual encounters with urban robots, as well as a study using a design probe to speculate about potential issues that may arise from the presence of urban robots. These studies lay the foundation for the subsequent design investigation by identifying scenarios in which casual collaboration between humans and urban robots may emerge, and by providing preliminary insights that inform the later design concept development. This part incorporates the following publications:

Chapter 3: Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Martin Tomitsch. (2024). Understanding the Interaction between Delivery Robots and Other Road and Sidewalk Users: A Study of User-generated Online Videos. In *ACM Transactions on Human-Robot Interaction (THRI)*.

Chapter 4: Xinyan Yu, Tram Thi Minh Tran, Yiyuan Wang, Kristina Mah, Yidan Cao, Stine S Johansen, Wafa Johal, Maria Luce Lupetti, Megan Rose, Markus Rittenbruch, Rodney G Zsolczay, and Marius Hoggenmüller. (2024). Out of Place Robot in the Wild: Envisioning Urban Robot Contextual Adaptability Challenges Through a Design Probe. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHIEA'24)*.

Part III - Design Investigation

This part bridges real-world situational encounters between urban robots and bystanders with design concepts aimed at facilitating casual collaborations between them. It begins with exploratory design methods that translate contextual insights into design considerations, which are then embodied in a series of concepts that facilitate casual collaboration. These design concepts were evaluated through either lab-based VR studies or a field study, providing insights into the effectiveness of the design concepts and the impact of such collaboration on people's attitudes toward robots. This part incorporates the following publications:

Chapter 5: Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch. (2023). Your way or my way: improving human-robot co-navigation through robot intent and pedestrian prediction visualisations. In *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction. (HRI'23)*

Chapter 6: Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch. (2024). From Agent Autonomy to Casual Collaboration: A Design Investigation on Help-Seeking Urban Robots. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems. (CHI'24)*

Chapter 7: Xinyan Yu, Marius Hoggenmüller, Martin Tomitsch. (2024). Encouraging Bystander Assistance for Urban Robots: Introducing Playful Robot Help-Seeking as a Strategy. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference. (DIS'24)*

Chapter 8: Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Martin Tomitsch. (2025). Feel the Presence: The Effects of Haptic Sensation on VR-Based Human-Robot Interaction. In *Proceedings of the 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN'25)*.

Chapter 9: Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Yiyuan Wang, Qiuming Zhang, Martin Tomitsch. (2025). Peek into the 'White-Box': A Field Study on Bystander Engagement with Urban Robot Uncertainty. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems. (CHI'25)*

Part IV - Discussion

This final part revisits the research questions and provides a conceptualisation of casual human-robot collaboration. It further reflects on the research methodologies and the research topic and outlines suggestions for future research directions.

2 Setting the Scene

2.1 Preamble

This chapter presents three bodies of literature that collectively construct the context and narrative of this thesis, clarifying the position it takes on human–robot collaboration and setting the scene for the studies that follow. It begins with an overview of how human–robot collaboration has evolved from its origins in industrial manufacturing to more recent calls to reconceptualise collaboration as something that emerges spontaneously and is socially situated within everyday encounters between humans and robots. The second section provides an overview of different types of robots in public spaces, introducing observational studies that document people's everyday encounters with them, alongside some theoretical frameworks that conceptualise these interactions as integral components of broader urban and social ecologies. The last section elaborates the stance this thesis takes on understanding what a robot is. It traces a trajectory from early speculative provocations of human-dependent robots to more recent design approaches of "weak robots," and other explorations that position robots as playful objects that bring moments of joy rather than serving purely instrumental functions.

While this chapter provides a general grounding for the thesis, it is important to note that the specific literature reviews relevant to the contexts and research problems addressed in each study are presented within their respective chapters that follow.

2.2 Human-Robot Collaboration

The earliest and probably most well-known form of human–robot collaboration emerged in the 1990s within industrial manufacturing contexts (Colgate et al., 1996; Matheson et al., 2019; Vysocky and Novak, 2016). In its early stages, industrial robots were designed to operate in separated spaces (Vysocky and Novak, 2016; Sauppé and Mutlu, 2015) (e.g. using safety fences (Jani, 2016), see Figure 2.1, right), executing tasks under the command of human operators. As advancements in technology enabled robots to sense and adapt to the behaviours of humans, it became possible to remove the physical barriers that once separated human and robot workspaces (Sauppé and Mutlu, 2015). The factory floor then turned into a shared space where human perceptual intelligence and robotic precision can work closely to pursue greater efficiency and productivity.

Fig. 2.1.: Comparison between a traditional industrial robot operating within a fenced enclosure (left) (Jani, 2016) and a robotic arm working alongside a human operator in a shared workspace (right) (Vysocky and Novak, 2016).

The ability of robots to collaborate safely and closely alongside humans also enabled their integration into increasingly diverse domains. In healthcare, robots can collaborate with medical professionals to assist in surgical operations (Colan et al., 2025), support telemedicine and remote care (Lyu et al., 2020), and perform logistical tasks such as disinfecting rooms (McGinn et al., 2021) or delivering medication (Zhu and Kaber, 2012). In service and hospitality settings, robots have become embedded into the workflow of frontline service providers, assisting in customer-facing tasks such as serving food in restaurants (Antony and Sivraj, 2018) and customer reception in hotels (Wu and Zhang, 2024). Furthermore, human–robot collaboration has also extended into creative domains, where robots are explored not merely as tools or assistants but as co-creators capable of engaging in shared acts of making and expression. This includes, for example, co-creative drawing with a robotic arm (Zhao et al., 2025), supporting designer ideation through collaborative sketching (Lin et al., 2020), and human–robot collaborative artistic performance (Thörn et al., 2020).

As robots move beyond the factory floor into increasingly diverse domains, the ways in which human–robot collaboration is defined and understood have also evolved. In the early conceptual work on HRC, Bauer et al. (Bauer et al., 2008) deliberately differentiate human–robot collaboration from the broader notion of human–robot interaction. While interaction refers to any form of action directed toward or influencing another agent, collaboration implies working together, with both partners *"committed to reach a common goal."* In their proposed framework, effective collaboration requires the formation of a *joint intention*, whereby the human establishes the goal and the role of the robot is to infer, adopt, and act upon this intention as its own, thereby creating a shared commitment that defines the collaborative process. Rooted in an *Industry 4.0* paradigm, such a traditional view envisions human-robot collaboration as a tightly coordinated partnership designed for precision and productivity. Such perspective heavily influenced how human factors are taken into consideration in HRC research. Hopko et al. (2022) reviewed sixty-one studies on HRC and found that most of them focused on a narrow set of performance-driven factors, such as trust, cognitive workload, and safety perception, revealing an enduring emphasis on task efficiency and system reliability. Gervasi et al. (2020) proposed a more comprehensive framework for evaluating HRC that extends beyond productivity and physical safety, emphasising the importance of considering the operator's psycho-physical state, such as emotional and cognitive factors. Moreover, their framework introduces an ethical dimension, recognising that HRC is embedded within a broader social context and must therefore account for social impact and social acceptance.

More recent work has shifted from viewing collaboration as a matter of task efficiency, where humans and robots engage in goal-oriented partnerships optimised for productivity, toward understanding it as an evolving, situated relationship shaped by the social and organisational contexts in which it occurs. Johansen et al. (2024) argue that HRC cannot be fully understood through performance metrics alone but must also consider how collaboration unfolds in real workplaces and everyday settings: how people assign roles to robots, adapt their routines around them, and make sense of their presence within existing social structures. Continuing on this departure from the *Industry 4.0* paradigm of HRC, Reeves et al. (2025) take up Johansen et al.'s call to re-contextualise human–robot collaboration by examining how collaboration is enacted in mundane, real-world encounters between people and robots on public streets. Drawing on ethnographical video analysis of interactions between pedestrians and delivery robots, they show that what appears as *"collaboration"* emerges through pedestrians' moment-by-moment adjustments that enable the robot to continue their path. Pedestrians continuously adapt their walking trajectories—slowing down, side-stepping, or forming "flow files" to follow or overtake delivery robots—so that these machines can proceed smoothly. Even when robots' movements are unpredictable or unintelligible, people spontaneously yield space or reconfigure their behaviour to maintain the flow of public life. They describe this as *accommodation work*, the subtle, situational efforts through which humans make robot actions eligible and fit them into the life of the street. This stands in contrast to traditional views of HRC, which treat collaboration as a technical property of robots that designed to ensure their ability to assist humans in achieving task goals. Their perspective further challenges instrumental or efficiency-based notions of collaboration, urging researchers to re-specify what collaboration means when robots are encountered in everyday social environments. Without attending to these subtle, improvised forms of coordination, robots in public spaces risk being perceived as intrusive or disruptive presences, interrupting the rhythms of public life rather than becoming part of its flow.

2.3 Robots in Urban Public Spaces

There has been rich exploration of how social robots can coexist naturally among and interact with people in dynamic, real-world public spaces. Back in the 1990s, early precedents such as *RHINO* (Burgard et al., 1999) and *Minerva* (Thrun et al., 1999), started to make their presence in (semi-)public spaces, engaging visitors in museums and providing tour guide (Figure 2.3, A). Pan et al. (2013) deployed social robots in a hotel lobby to greet guests and engage them in short, informative conversations about hotel services. Their results showed that robots attracted significantly more attention than either human staff or static displays. EU *MuMMER* project deployed the *Pepper* robot in shopping malls to interact with visitors and provide a more engaging shopping experience (Foster et al., 2016), through behaviours as greeting customers, offering information, or performing playful activities like jokes and games.

Beyond offering services and enhancing social engagement, some work has also explored how social robots can perform regulatory and persuasive roles in public settings. Schneider et al. (2022) deployed a humanoid robot in a Japanese shopping mall that admonished pedestrians for using smartphones while walking (Figure 2.3, B), a common safety concern in urban environments. Their results indicated that the majority of smartphone users stopped using their phones after the robot's simple admonishment was refined into a more socially aware form of persuasion. During the COVID-19 pandemic, Beck et al. (2021) deployed a hand sanitiser robot in a

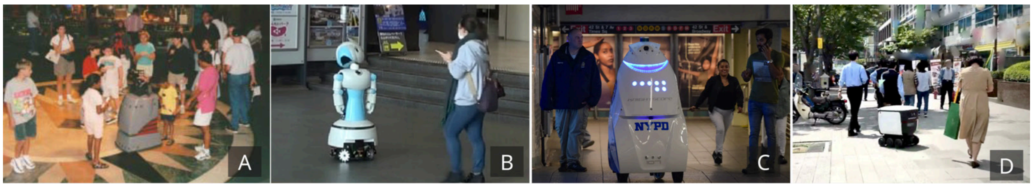

Fig. 2.2.: Examples of robots in public urban environments. (A) Minerva museum tour-guide robot interacting with visitors (Thrun et al., 1999); (B) Pepper robot dis-encouraging people looking at phones while walking (Schneider et al., 2022); (C) Knightscope K5 patrolling a station (Ye and Land, 2024); (D) Delivery robot navigating a pedestrian street. (Cheon and Shin, 2025)

university lobby to encourage hand hygiene by approaching passersby and using verbal prompts. Their results showed that people were more willing to comply when the robot spoke in a polite tone and moved at a slower speed.

Different from social robots that are designed to actively engage passersby and provide direct services, some robots in public spaces operate more peripherally, going about their tasks without explicitly interacting with people around them. Early examples such as the EU *DustBot* project integrated autonomous service robots into urban environments to perform civic tasks such as garbage collection and street cleaning (Ferri et al., 2011). Since 2016, the United States has begun to deploy security robots, *Knightscope K5* (Figure 2.3, C), to patrol plazas, transport stations, and shopping centres for surveillance and deterrence (Ye et al., 2024; Ye and Land, 2024). More recently, autonomous delivery robots have been increasingly deployed in countries across the world (Cheon and Shin, 2025; Weinberg et al., 2023) to provide last-mile delivery services for food and consumer goods. The flagship delivery robot company, *Starship Technologies*, recently announced that its fleet has completed over eight million deliveries worldwide (Starship Technologies, 2025).

Compared to social robots that are explicitly designed for human engagement, these task-oriented robots in public spaces typically feature limited interaction modalities and spend most of their operational time roaming around urban environments. Consequently, they are frequently encountered by bystanders who are not their intended users, leading to incidental, unplanned human–robot encounters. These encounters, rather than planned interactions with primary users, form the focus of this thesis. Recent HRI research has begun to highlight the importance of studying these overlooked forms of interaction with non-users, whom Rosenthal-von der Pütten et al. (2020) refer to as incidentally co-present persons *(InCoPs)*, arguing that this largely neglected group is becoming increasingly relevant in public robot deployments.

Recent observational studies of urban robots offer a growing body of knowledge about how such encounters unfold in practice and the potential frictions that may arise. Weinberg et al. (2023) conducted field observations of delivery robots operating on public sidewalks and found that pedestrians, who often had little understanding of the robots, often "crafted stories about their purpose and function" in order to make sense of them. The study also documented how the robots caused distractions and obstructions for other road users, highlighting the need to design more effective communication and interaction strategies. Nielsen et al. (2022) highlighted the fluidity of human roles around robots, pointing out that interaction roles, such as users, observers and *InCoPs*, are not fixed but can dynamically shift as people move in and out of engagement during an encounter. To ensure these shifts, they pointed out that robots deployed in public spaces should be designed to support unguided interaction, without requiring prior training, familiarisation, or technical assistance.

The video-ethnographic study of delivery robots (Pelikan et al., 2024) shows that most encounters on public streets take the form of subtle, moment-to-moment adjustments (e.g., slowing down, stepping aside, or briefly altering walking trajectories), rather than explicit interaction. The authors further note that robots are frequently treated as *"unremarkable,"* with pedestrians often ignoring them and incorporating them into the flow of everyday street life as just another element of the environment. Similar to the *accommodation work* noted by Pelikan et al. (2024), the walk-along observations of delivery robots by Cheon and Shin (2025) likewise show that their operation is largely enabled by human accommodation, with pedestrians repeatedly granting the robot the *"courtesy"* of passage. Beyond these subtle, low-effort adjustments, bystanders are also sometimes observed to step in to offer active assistance when robots encounter difficulties. This includes, for example, passersby pushing delivery robots forward when they become stuck in snow (Dobrosovestnova et al., 2022), or moving obstacles out of the robot path to allow it to continue navigating (Weinberg et al., 2023; Pelikan et al., 2024).

Building on these empirical accounts of how robots are encountered in public space, a growing body of conceptual work has begun to offer new theoretical lenses for understanding robots not as isolated artefacts, but as situated actors embedded in the social, spatial, and cultural dynamics of the city. Nagenborg (2020) sugguests that robots deployed in cities must be understood in relation to the qualities that make urban spaces socially and ethically meaningful. He introduces the notion of *"cityness"* to emphasise that the integration of robots should not only address functional or technical concerns, but also preserve the civic values of public space. Pelikan et al. (2025) extend this line of thought by drawing on urban sociology, particularly William H. Whyte's *Street Life Project* (Whyte et al., 1980), to argue that robots do not simply occupy space, but participate in the ongoing social production of place. They propose a framework that foregrounds four interrelated dimensions that shape how robots become integrated into everyday urban life, including *localism*, how robots fit the identity and culture of a place; *environments*, the physical and infrastructural conditions around them); *activities*, the everyday practices unfolding in that setting, and *sociability*, how people collectively interpret and negotiate around robots. Dobrosovestnova et al. (2025) propose a shift from seeing people as users to viewing them as actors occupying different subject positions in relation to robots. Their framework maps these roles across three interlinked ecologies: *service ecology*, where robots function as technical systems delivering service; *street–life ecology*, where robots move among people and become part of everyday urban co-presence; *public discourse ecology*, where robots become a matter of public concern subject to media attention, regulation, civic debate.

2.4 Robots Beyond Automation

This section elaborates the stance this thesis takes on understanding what a robot is, and how this position shapes the investigation that follows. The word robot originates from the Czech term *robota*, meaning *"forced labour"* or *"compulsory service."* First introduced by playwright Karel Čapek in his 1920 play R.U.R. (Rossum's Universal Robots) (Capek, 2004), robots were portrayed as tireless mechanical labourers designed to serve humans. While the form and capabilities of robots have evolved over the past century, this foundational idea of robots as entities designed to serve people remains deeply embedded in contemporary robotics. This is evident not only in industrial robots that work continuously on assembly lines (Hägele et al., 2016) and restaurant robots that autonomously deliver meals to customers (Seyitoğlu and Ivanov, 2022), but also in social robots that provide companionship, emotional support, and caregiving (Vanderborght et al., 2012; Kanda et al., 2012). In all of these cases, robots are positioned as tools, or helpers, whose primary purpose is to support human goals.

In contrast to this traditional view, a growing body of work challenges the one-directional framing of robots as self-sufficient agents that perform work on behalf of humans, instead designing robots that depend on people to function. One of the earliest and most influential examples is *Needy* from the speculative design project *Technological Dreams Series: No. 1* by Dunne and Raby, 2013, which imagines robots not as efficient helpers but as emotionally and socially demanding

Fig. 2.3.: (A) The Steam Man of the Prairies (Ellis, 1868), illustrating an early imagination of robots as mechanical labourers; (B) *Tweenbot*, a human-dependent robot that depends on passersby for navigation (Kinzer, 2009); (C) *iBones*, a "weak robot" that hands out tissues through visibly hesitant and imperfect gestures (Nishiwaki et al., 2017); (D) *Woodie*, a slow-moving chalk-drawing robot designed to foster playful, collaborative placemaking in public space (Hoggenmueller et al., 2020b).

entities that require human care and companionship. *Tweenbots* (Kinzer, 2009) were cardboard robots released into New York City parks that could only move forward and relied on passersby to manually steer them toward their destination. Rather than demonstrating robotic autonomy, the project revealed how a simple, vulnerable robot could spark spontaneous human care and collective action in public space, positioning collaboration not as a feature of the robot, but as an emergent property of people around it. *hitchBOT* (Smith and Zeller, 2017) similarly inverted the conventional model of robotic autonomy by sending a stationary, speech-enabled hitchhiking robot across countries with no moving capability. Rather than evaluating efficiency or task performance, *hitchBOT* functioned as a cultural probe that invited reflection on social cooperation, vulnerability, and the kinds of relationships people are willing to form with a robot that relies on their help. The *ACE (Autonomous City Explorer)* project extends this trajectory from a more pragmatic angle. The researchers developed a navigation architecture in which the robot could only reach its destination by asking passers-by for directions, and evaluated both the intuitiveness of the interface and people's willingness to assist the robot in a field deployment. The trial showed that the robot successfully completed its journey entirely through human support, and that most pedestrians were willing to help when approached by the robot.

Building on these provocations, HRI designers and researchers have further developed the idea of human-dependency and operationalised it as tangible design strategies, giving rise to a recent design philosophy known as *weak robots* (Okada, 2023), robots that are designed to serve people yet are intentionally imperfect and require human accommodation. The *Social Trash Box* (Yamaji et al., 2010), for example, does not have the ability to pick up litter by itself. Instead, it approaches nearby people in a teetering manner and makes a slight stooping motion, inviting passersby to complete the task for it. *iBones* is a robot that hands out tissues in public space, but rather than completing its task efficiently and smoothing, it performs it in a visibly awkward and hesitant manner (Nishiwaki et al., 2017). Through slow, imprecise movements, slight wobbles, and incomplete handing out gestures, the robot intentionally interrupts automation and turns a simple service task into a shared interaction. A similar strategy has also been applied in conversational robots. The *Talking-Bones* robot (Onoda et al., 2019), is designed to tell traditional stories to children, but it intentionally "forgets" key words, prompting children to step in and help complete the narrative. Their study showed that this intentional weakness not only elicited empathy and enrich engagement, but also shifted the learning dynamic, as children began teaching the robot and, in doing so, learned the stories themselves.

In addition to dependency and weakness, some robots challenge the dominant assumption that robots must serve a functional purpose. Rather than performing tasks or fulfilling instrumental goals, they are designed simply to bring moments of joy, curiosity, or playfulness into public life, with no functional purpose beyond the experience they create. *Woodie*, for example, is a slow-moving chalk-drawing robot deployed in urban space to explore how robots can function not as efficient service machines but as catalysts for playful, collaborative placemaking (Hoggenmueller et al., 2020b). By drawing simple shapes on the ground with coloured chalk, Woodie invited passersby to pause, watch, and even join in by adding their own drawings, transforming an ordinary street into a shared creative canvas. Similarly, *BubbleBot* roams public space bursting bubbles at passersby (Lee and Jung, 2020), creating small moments of magic and fostering serendipitous encounters among strangers.

2.5 Summary

In summary, as robots transition from controlled industrial environments into urban public spaces, traditional understandings of human–robot collaboration that rooted in shared goals, joint intentions, and efficiency become insufficient. At the same time, provocative conceptual and design-oriented work has begun to challenge the view of robots as self-sufficient tools that operate for humans, but rather as relational actors embedded in shared public life that invite care, negotiation, or shared meaning-making. This shift is echoed in recent design advocacy for "robot citizenship" (Lupetti et al., 2019), which reframes robots not by their functional capabilities but by their roles, relations, and participation within urban communities (Lupetti et al., 2019).

Following this perspective, this thesis frames collaboration between bystanders and robots in public spaces as an issue of coexistence rather than service provision, one concerned with how interdependence, care, and mutual adjustment are negotiated through design, and how more reciprocal human–robot relationships may emerge as a result. At the same time, it translates the ideas of human-dependent robots and "weak robots" into a pragmatic stance, focusing on real-world situations in which such collaboration becomes necessary for the smooth operation of robots in public spaces, and examining how to design interactions that support spontaneous, casual collaborations arising in everyday encounters. This perspective sets the foundation for the empirical studies that follow and motivates a renewed understanding of how human–robot collaboration unfolds in spontaneous, situated encounters in public urban spaces.

Part II

Contextual Research: Understanding Urban Robots in Public Spaces

3 Understanding the Interaction between Delivery Robots and Other Road and Sidewalk Users: A Study of User-generated Online Videos

3.1 Preamble

Xinyan Yu, Tram Thi Minh Tran, Yiyuan Wang, Marius Hoggenmueller, Martin Tomitsch (2023). Understanding the Interaction between Delivery Robots and Other Road and Sidewalk Users: A Study of User-generated Online Videos. In *ACM Transactions on Human-Robot Interaction (THRI)*.

This chapter presents an online ethnography of 117 user-generated videos from TikTok and their associated 2,067 comments. It primarily addresses RQ1 *"In what situations does casual collaboration between urban robots and bystanders unfold? What design opportunities are emerging from these situations?"* by identifying scenarios in which collaborations emerge between bystanders and urban robots. These findings provide a contextual foundation for the design investigations presented in the subsequent studies in III. The identified scenarios are as follows:

- In close encounters, pedestrians and urban robots engage in path negotiation to navigate around each other.(scenario explored in Chapter 5)
- When robots experience physical incapabilities (e.g., getting stuck), they require bystanders to step in and help. (Chapter 7)
- Faced with technological limitations(e.g., uncertainties), robots rely on bystanders to offer guidance(Chapter 9 and Chapter 8).

In addition, the analysis of people's reactions towards robots and comments generates design considerations for the interaction between urban robots and bystanders, providing insights into RQ2 *"How can we design interactions that facilitate casual collaboration between bystanders and urban robots?"*.

This chapter was originally published as an article in the ACM Transactions on Human-Robot Interaction. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

3.2 Abstract

The deployment of autonomous delivery robots in urban environments presents unique challenges in navigating complex traffic conditions and interacting with diverse road and sidewalk users. Effective communication between robots and road and sidewalk users is crucial to address these challenges. This study investigates real-world encounter scenarios where delivery robots and road and sidewalk users interact, seeking to understand the essential role of communication in ensuring seamless encounters. Following an online ethnography approach, we collected 117 user-generated videos from TikTok and their associated 2,067 comments. Our systematic analysis revealed several design opportunities to augment communication between delivery robots and road and sidewalk users, which include facilitating multi-party path negotiation, managing unexpected robot behaviour via transparency information, and expressing robot limitations to request human assistance. Moreover, the triangulation of video and comments analysis provides a set of design considerations to realise these opportunities. The findings contribute to understanding the operational context of delivery robots and offer insights for designing interactions with road and sidewalk users, facilitating their integration into urban spaces.

3.3 Introduction

The deployment of autonomous delivery robots (ADRs) is becoming increasingly prevalent in urban spaces, holding promise for enhancing last-mile delivery efficiency (Marks, 2019), as well as reducing energy consumption and emissions (Figliozzi and Jennings, 2020). ADRs encompass various robotic platforms, including self-driving vehicles, autonomous delivery pods, and sidewalk delivery robots, also known as personal delivery devices (PDDs). This study focuses on small-scale PDDs weighing between 20 and 250 kilograms and operating at a maximum speed of 12 m/s, which often share sidewalks with other sidewalk users (Minnesota Department of Transportation, 2021).

While other types of mobile robots, such as assistive robots (Lee and Riek, 2018) or cleaning robots (Forlizzi, 2007), typically operate in closed-off and more predictable environments (e.g., workplaces or domestic spaces (Graaf et al., 2019; Zhang et al., 2020)), delivery robots must navigate complex and dynamic urban traffic environments and interact with a diverse range of road and sidewalk users, including pedestrians, cyclists, and vehicle users (Grush, 2022). This requires delivery robots to be highly adaptable and capable of handling unexpected situations, which can pose challenges to their smooth deployment. Although advances in robotics technology continue to enhance the operational capability of delivery robots, potential challenges during real-world deployment are difficult to fully anticipate during the robot development process (Srinivas et al., 2022). To shed light on the practical considerations of these delivery robots, recent studies have turned their attention to the real-world deployment of delivery robots, for example, evaluating traffic accessibility (Arntz et al., 2023; Plank et al., 2022; Dobrosovestnova et al., 2022) or observing people's interactions with these robots (Abrams et al., 2020; Weinberg et al., 2023; Vroon et al., 2020; Gehrke et al., 2023).

When designing ubiquitous technologies for urban contexts, it is crucial to consider non-users as stakeholders (Tomitsch, 2018). When delivery robots operate in public spaces, they could potentially affect incidental road and sidewalk users who encounter the robot without intending to interact with it, who have been referred to as Incidentally Co-present Persons (InCoPs) (Rosenthal-von der Pütten et al., 2020). In situations such as unmarked crossings and shared spaces where formal traffic rules are lacking, road and sidewalk users often rely on social norms to convey intentions and anticipate behaviours (Prédhumeau et al., 2023; Rasouli and Tsotsos, 2020). To navigate such complex environments effectively, delivery robots and other autonomous vehicles (AVs) must be equipped with the ability to communicate with other road and sidewalk users and follow social norms (Schött et al., 2023; Wang et al., 2022). Numerous studies have focused on probing driver-pedestrian interaction patterns and designing external human-machine interfaces (eHMIs) for traditional road conditions (Dey et al., 2020). However, the communication requirements for delivery robots extend beyond these contexts, as they operate more frequently in unstructured areas such as sidewalks and shared pedestrian zones and often encounter sidewalk users in close proximity. Furthermore, the lack of transparency in AI-driven systems can create difficulties in understanding the behaviours of delivery robots, negatively impacting the quality of interaction and diminishing people's trust and acceptance of the technology (Graaf et al., 2018; Schött et al., 2023).

In September 2022, a video capturing a delivery robot ignoring police tape and barging through a crime scene went viral on social media, sparking discussion about the readiness of such robotics technology in real-world settings. This incident is symbolic of the many scenarios that delivery robots need to address in real-world operations and underscores the need for human-robot interaction (HRI) research to study how these systems interact with people in real-world settings. Delivery robot technology companies have been increasingly conducting pilot programs in public spaces, such as *Starship robot*[1] pilot programs across various U.S. campuses and Europe, as well as *Kiwibot*[2] pilot program in Pittsburgh (Grush, 2022; Sawers, 2018; Gehrke et al., 2023), resulting in a notable presence of delivery robots in urban environments. Consequently, there is a growing amount of user-generated content on social media about people's encounters with these robots. These resources provide valuable data for HRI researchers to study real-world deployment scenarios and people's attitudes towards delivery robots, which can offer insights for designing better external interfaces to facilitate interactions between road and sidewalk users and delivery robots (Nielsen et al., 2022).

To inform the interaction design of delivery robots through insights from real-world deployment scenarios and the public's attitudes toward delivery robots, we conducted an online ethnographic study. Our study utilised a systematic search approach to collect user-generated videos depicting delivery robot operations in urban spaces on video-sharing platform *TikTok*[3], along with their corresponding comments. We conducted video content analysis, identifying scenarios in which effective communication from the delivery robot is essential to facilitate smooth interactions between the robot and sidewalk users, as well as people's behavioural patterns when encountering robots. Furthermore, through a thematic analysis of the corresponding comments on these videos, we identified several themes regarding people's attitudes toward delivery robots, including acceptance, perceptions, and information needs. This study makes twofold contributions. First, the identified scenarios delve into potential design opportunities to augment communication between delivery robots and other road and sidewalk users in complex urban contexts and situations, going beyond the conventional focus on path negotiation. Second, our triangulated analysis of videos and comments provides insights into

[1]`https://www.starship.xyz/`, *last accessed: April 2023*
[2]`https://www.kiwibot.com/`, *last accessed: April 2023*
[3]`https://www.tiktok.com/`, *last accessed: April 2023*

design considerations for the interaction design between delivery robots and other road and sidewalk users.

3.4 Related Work

3.4.1 Delivery Robots in Urban Environments

ADRs have become one of the latest personal delivery innovations, promising to provide more efficient, environmental-friendly, and flexible delivery options (Figliozzi, 2020; Jennings and Figliozzi, 2019), with a projected growth to fulfill 85% of last-mile deliveries by 2025 (Marks, 2019). This emerging technology has spurred a growing body of academic literature, including works on operational improvements such as efficiency optimisation (Sonneberg et al., 2019) and human-aware social navigation (Mavrogiannis et al., 2023), economic perspectives such as consumer acceptance of delivery robots (Kapser and Abdelrahman, 2020; Abrams et al., 2021), and regulatory frameworks (Hoffmann and Prause, 2018).

The potential of delivery robots to enhance the efficiency of last-mile delivery has been demonstrated by promising results from pilot programs launched by companies such as *Starship Technologies* across the United States and Europe. These programs have reported average delivery times of less than 15 minutes in California, suggesting that delivery robots could serve as a viable alternative to traditional delivery methods (e.g., carried out by delivery drivers) (Sawers, 2018). However, despite their potential benefits, issues arise due to their use of shared spaces with other road and sidewalk users, concerning matters such as traffic congestion, hindered pedestrian mobility, increased risks of collisions, creating accessibility barriers for people with disabilities (Marks, 2019; Koh and Yuen, 2023; Gehrke et al., 2023; Bennett et al., 2021), and the potential to induce irritation, anxiety, or frustration among people (Boll et al., 2019). Thus, there is a growing need to study the impact these delivery robots have on co-present road and sidewalk users. Rosenthal-von der Pütten et al. (2020) have stressed the importance of a holistic, human-centred approach that accounts for the interactions with these bystanders. Several existing observation studies have provided a brief overview of people's reactions toward these robots in public environments, however, there has been little research on how they interact with delivery robots in public traffic settings.

Several observation studies were conducted through a Wizard of Oz (WoZ) approach (Dahlbäck et al., 1993), wherein operators remotely controlled the robot's navigation while researchers observed people's interactions with the robots in public spaces. Vroon et al. (2020) pointed out the shortcomings of existing social navigation approaches in catering for the dynamic interactions between delivery robots and pedestrians. Taking a different approach, they conducted a field observation study using a remote-controlled robot that deliberately ignores people in order to elicit actual conflicts in real-world contexts. Their findings suggested that individuals tended to actively avoid the robot or pause to observe it due to the novelty of the robot's presence. Abrams et al. (2020) built a delivery robot mock-up controlled by a human operator and conducted a field observation study to examine human-robot interactions in an urban setting in Aachen, Germany. Their study found that children often exhibited exploratory behaviours in response to the robot, while some adult pedestrians demonstrated a lack of acceptance or resistance towards the presence of these delivery robots on sidewalks. Following a similar approach, Mierlo (2021) conducted a field observation on a sidewalk in a park in Utrecht. Their observation indicated that the majority of people ignored the presence of the prototypical robots, while a smaller percentage of people exhibited a fleeing response when encountering them.

In addition to WoZ studies, pilot delivery robot programs provide researchers with opportunities to observe the real-world deployment of these robots. Gehrke et al. (2023) analysed field-recorded videos captured during a one-week delivery robot pilot program conducted on the Northern Arizona University campus. They found the presence of delivery robots disrupted the mobility and efficiency of other road and sidewalk users, as they had to modify their paths to avoid potential collisions with the robots. Dobrosovestnova et al. (2022) conducted a field study in Tallinn, Estonia, to examine the operation of delivery robots in challenging conditions (i.e., snow-covered sidewalks). The researchers found overall positive reactions from people towards the robots, and in instances where the robots got stuck in the snow, some people voluntarily assisted the robots to resume their operation. In a recent observation study conducted in Pittsburgh (Weinberg et al., 2023), researchers found that delivery robots occasionally caused distractions and obstructions with sidewalk users. Similar to Dobrosovestnova et al. (2022)'s study, they also observed instances where people voluntarily helped immobilised robots.

3.4.2 Autonomous Vehicle-Pedestrian Communication

Developing external interfaces to facilitate interactions between autonomous vehicles, ranging from large transportation vehicles to smaller mobile robots, and other road users is crucial for building trust in automated systems (Hussein et al., 2016) and has been a key focus of research in the field of pedestrian-vehicle interactions. Extensive research has been conducted on exploring a wide range of eHMIs to effectively communicate AVs' status, intentions (Dey et al., 2022; Weber et al., 2019) and awareness (Verstegen et al., 2021; Mahadevan et al., 2018) to pedestrians, leveraging various modalities, such as on-road projections (Nguyen et al., 2019; Löcken et al., 2019), on-vehicle displays (e.g., LED light bands (Dey et al., 2022)) and augmented reality (AR) (Tran et al., 2022). However, despite the wide range of communication strategies and channels that have been investigated, the majority of these studies are limited to traditional traffic scenarios, such as uncontrolled zebra crossings (Dey et al., 2020; Colley et al., 2020b), and did not encompass the broad range of scenarios in which delivery robots and other road and sidewalk users may interact in shared spaces (Karndacharuk et al., 2013).

Delivery robots, in contrast to large transportation vehicles, frequently navigate sidewalks in close proximity to a broader range of road users and sidewalk users (Weinberg et al., 2023). This unique operational context presents communication challenges that extend beyond mere path negotiation at intersections, which are typically the main focus of autonomous vehicle-pedestrian communication design concepts. However, in comparison to the extensive body of work on communication design methods for large transportation autonomous vehicles, research specifically focused on the design of communication for delivery robots is relatively limited. Kannan et al. (2021) acknowledged this gap and conducted an online survey to investigate the comprehensibility of display and light-based interfaces that convey the delivery robot's navigational intent to pedestrians under common navigation scenarios. Inoue et al. (2022) designed an AR display that showed real-time information about a delivery robot such as the operation status, destination, and speed, and found that it positively reduced user anxiety around them. However, the design was evaluated by pedestrians standing at a fixed position, which limits its real-world applicability. This limitation has also been recognised in a recent literature review (Prédhumeau et al., 2023), which highlighted that the majority of empirical studies on AV-pedestrian communication have primarily focused on lateral interactions at pedestrian crossings. The review pointed out the need for investigating more diverse interaction configurations of AV-pedestrian interactions in shared spaces. Furthermore, the communication needs of road users other than pedestrians, such as car users, have been largely overlooked in the existing literature. Therefore, a more comprehensive investigation is needed to understand the challenges and opportunities for interaction between delivery robots and other road and sidewalk users in these dynamic and complex environments.

3.4.3 Social Media as a Resource for HRI Research

The examination of social media content (Postill and Pink, 2012)—commonly also referred to as online ethnography (Tomitsch et al., 2018)—has emerged as a valuable approach in HRI research for assessing public attitudes and perceptions toward robots, as well as exploring human-robot interactions in real-world settings (Strait et al., 2017; Hover et al., 2021; Zeller et al., 2020; Nielsen et al., 2022; Dobrosovestnova et al., 2022; Savela et al., 2024). Strait et al. (2017) conducted a study examining the commentary on *YouTube*[4] videos depicting robots to investigate the public's opinions regarding the emergence of highly humanoid robots compared to robots with more prototypical robotic appearances. The results were consistent with the theory of the uncanny valley (Ho and MacDorman, 2010), as people more frequently expressed aversion towards highly humanoid robots. Moreover, the discourse observed on online platforms highlighted concerns regarding the potential 'technology takeover' associated with the robots' realistic appearances. Following a similar approach, the study conducted by Hover et al. (2021), analysed online comments on videos that featured robots with varying degrees of humanlike attributes and gender to investigate how people perceive and interact with humanoid robots. In the context of delivery robots, Dobrosovestnova et al. (2022) analysed online comments as a supplementary resource to their field observation study on delivery robots facing operational challenges on snow-covered sidewalks. They pointed out the significance of considering ethical implications when commercial technology relies on the assistance of bystanders to accomplish its tasks, as reflected in the online comments. Lee and Toombs (2020) analysed online discourse about delivery robots in a university's subreddit, shedding light on people's perception of delivery robots as objects of affection and social members. However, their study had demographic limitations since it focused on a specific group of people (i.e., campus students from the university where the delivery robot was deployed) and the social media platform they investigated.

Apart from textual comments and posts, video-sharing platforms such as *YouTube* or *TikTok* have become an increasingly popular source of empirical data, utilised by many HCI researchers to gain insights into people's natural interactions with technology outside the lab (Blythe and Cairns, 2009; Paay et al., 2015; Bartolome and Niu, 2023). This is particularly valuable in the context of shared spaces, where human-robot encounters are often casual and spontaneous, and natural and intuitive reactions to robots are difficult to study in a controlled laboratory setting (Abrams et al., 2020). Thus, behaviours observed in user-generated videos

[4] `https://www.youtube.com/`, *last accessed: April 2023*

may have emerged more naturally compared to those in controlled lab studies, where participants are assigned tasks to complete (Nielsen et al., 2022). Nevertheless, leveraging social media data comes with inherent limitations, such as the lack of demographic information about content creators (Strait et al., 2017) and potential bias in commenting (Khan, 2017). Moreover, some researchers raised concerns that social media videos might be performative or staged, thus not accurately representing natural behaviours (Paay et al., 2015).

So far, the analysis of user-generated videos in HRI research is relatively rare. To the best of our knowledge, the recent study by Nielsen et al. (2022) is the only online ethnography study that analyses user-generated *YouTube* videos to investigate unguided interactions between people and public service robots. While their study provides valuable insights for designing service robots to operate effectively in complex and unstructured environments, they solely focus on contexts in which the robot intends to provide service to people and is limited to indoor settings (e.g., shopping malls and train stations). Our study, on the other hand, aims to investigate casual encounter scenarios between delivery robots and pass-by road users (i.e. without intention in engaging in interactions) in urban traffic settings.

3.4.4 Summary

In summary, the deployment of delivery robots and the interactions between these robots and other road and sidewalk users in shared urban spaces pose complex challenges. While progress has been made in optimising robot efficiency (Sonneberg et al., 2019), implementing social navigation (Mavrogiannis et al., 2023), and developing eHMIs for traditional traffic settings (Dey et al., 2020; Colley et al., 2020a), there is a need for a more comprehensive understanding of the dynamic and complex interaction scenarios that emerge through real-world deployments of delivery robots (Prédhumeau et al., 2023). While delivery robot operations are currently limited to small-scale pilot studies (Weinberg et al., 2023; Grush, 2022; Sawers, 2018; Gehrke et al., 2023), this presents geographical and temporal constraints for researchers aiming to observe their real-world operations. Moreover, observing people's natural and spontaneous behavioural responses to encountering robots is challenging in lab studies, where participants are typically given particular tasks to perform (Nielsen et al., 2022). Our work addresses these challenges by leveraging social media content to identify real-world interaction configurations and gain insights into people's attitudes toward delivery robots. This analysis explores the design contexts for interactions between delivery robots and other road and sidewalk users, providing insights to inform the design of effective interaction strategies.

3.5 Methodology

To address the current lack of empirical investigation into the real-world deployment of delivery robots, we conducted an online ethnography study (Tomitsch et al., 2018) to analyse user-uploaded videos on *TikTok* that capture encounters between delivery robots and the recording person or other surrounding people. We analysed those videos to identify real-world scenarios which necessity communication of delivery robots to facilitate smooth interactions with road and sidewalk users. Additionally, we conducted a thematic analysis of comments in response to videos to gain further insights into people's attitudes towards delivery robots and how these can inform the interaction design of delivery robots.

In sum, our online ethnography was guided by the following research questions:

RQ1: What are the real-world encounters documented online that reflect scenarios in which communication between delivery robots and road and sidewalk users is necessary?

RQ2: What are the public's attitudes towards delivery robots, and how can these attitudes inform the interaction design of delivery robots?

3.5.1 Data Collection

Initial Search Phase

To ensure a systematic and comprehensive approach, we conducted an initial search across diverse video-sharing platforms such as *TikTok* and*Youtube*, as well as the search engine *Google*, to obtain a broad overview of videos depicting interactions with delivery robots. After trialing various combinations of keywords across these platforms, we selected *TikTok* as the most suitable platform for our study due to its extensive collection of user-generated content that captures genuine and spontaneous encounters with delivery robots. Furthermore, we decided on a search keyword strategy of combining technology-related terms and case-specific keywords (as proposed in prior research studies (Komkaite et al., 2019; Anthony et al., 2013)), and ultimately settled on the search terms *delivery robot + lost* and *delivery robot + why*. To broaden the scope of the search, the names of three popular delivery robots,

Tab. 3.1.: Delivery robots included in the study

Name	Image	Level of autonomy*	Communication modality	Main deployment regions**
Starship		Level 4 to Level 5	Natural language speech, sonic notification, flashing lights	The U.S. (e.g., California, Washington, D.C.)and Europe (e.g., Helsinki, London)
Kiwibot		Level 2 to Level 3	On-screen displayed eyes	Cities and college campuses of the U.S. such as California, Arizona, and Florida
Tiny Miles		Level 2 to Level 3	On-screen displayed eyes, flashing lights	Cities in the U.S such as North California and Miami
Coco		Level 4	Flashing light, sonic notification	Cities in the U.S such as Santa Monica, Los Angeles, and Miami
Postmates		Level 4	Led-lights in eye shape, flashing light	Cities in the U.S such as Los Angeles, San Francisco, and Miami
Scout		Level 4	Flashing light	Cities in the U.S such as California, and Atlanta, Georgia

* The autonomy level information presented in the table was obtained from the official websites of the respective technical companies associated with each robot, the autonomy level classification is based on the definitions provided by SAE International (2021).
** The deployment area information presented in the table was obtained from the official websites of the respective technical companies.

including *Starship robot*, *Coco robot*[5], and *Postmates robot*[6] were included as alternative search terms for *delivery robot*. To ensure that our search was comprehensive yet efficient, we followed the stop criterion suggested in previous research (Anthony et al., 2013; Nielsen et al., 2022) and stopped the search after reviewing at least 25 successive videos that were deemed irrelevant.

The search was conducted by the first author between November 5^{th} and November 12^{th}, 2022, and yielded an initial set of 612 video samples. Meta information for each video was recorded during the search process, including the link to the video, the upload date, the comments, the video's views, and the number of likes. Table 3.1 provides an overview of all the delivery robots included in the dataset.

Video Screening and Filtering

After collecting the initial video samples, we conducted two rounds of screening and filtering to ensure the quality of the data. During the first round, duplicated

[5] `https://cocodelivery.com/`, *last accessed: April 2023*
[6] `https://serve.postmates.com/`, *last accessed: April 2023*

and inaccessible videos were removed following the common criteria used in the initial filtering process (Rotman and Preece, 2010; Nielsen et al., 2022; Komkaite et al., 2019; Paay et al., 2015), which resulted in 475 videos. In the second round, we adopted similar exclusion criteria used in (Komkaite et al., 2019; Nielsen et al., 2022) to exclude videos that did not feature a delivery robot in operation, or contained advertisements, staged acts, or non-English speech. The exclusion of non-English videos, totalling 17, was based on concerns regarding potential misinterpretation and loss of originality due to translation. Additionally, videos with excessive editing, disrupted chronological order (Jewitt, 2012), or rapid short clips were removed, following the concerns raised by Nielsen et al. (2022) regarding the impact on the validity and neutrality of the recording. Two videos that were no longer accessible during the later analysis process were also excluded. In the end, the data set consisted of a total of 117 videos that were eligible for analysis.

Comments Extracting

To gain further insights into the public's attitudes towards delivery robots, we extracted the top 50 independent comments (i.e., comments that are not replies or threads) from each of the 117 eligible videos. We decided on this criterion to address the wide variation in comment counts across videos and to create a dataset that is both rich and manageable, thus allowing us to maintain a balance between in-depth analysis and practicality. This comment extraction protocol was adapted from previous online ethnography studies in HRI (Hover et al., 2021; Strait et al., 2017). To ensure the richness and diversity of video scenarios, we included videos with a lower number of comments, even though similar studies tend to exclude such videos if they have fewer comments than the number they aim to extract. Thus, in cases where the number of comments was less than 50, all eligible comments were extracted.

To standardise the dataset, the comments were further processed by all three coders (i.e., the first, third, and fourth authors) based on a set of exclusion criteria agreed upon by consensus. Comments that met the following exclusion criteria were excluded: (1) non-English comments; (2) comments unrelated to robots; (3) comments with ambiguous meaning or reference, which could hinder coders from accurately interpreting the underlying sentiments; and (4) comments that contained jokes which, upon discussion and agreement among all coders, were determined not to reflect people's true attitudes. The filtering process resulted in a final dataset of 2067 comments.

Tab. 3.2.: Example of video annotation

Scenario description	Video recorder	People captured in video
The robot operates on the sidewalk (00:00)	-	-
Stops at red traffic lights (00:10)	The recorder shouts with surprise: 'Oh my god, it's crazy. It stops at the right light!' (00:11)	A pedestrian smiles to and agrees with the recorder (00:11)
-	-	A pedestrian pretends to kick it (00:15)
Moves when light turns green (00:21)	-	A pedestrian turns his head to look at it (00:23)

3.5.2 Data Analysis

This section outlines the methodology used in the study for analysing both the video content and the comments posted under the videos. The methodology includes the use of thematic analysis (Braun and Clarke, 2006) to analyse and look for patterns in the comments and an approach inspired by open coding (Corbin and Strauss, 2014) to identify the encounter scenarios in the video content.

Identifying the Scenarios

We began the video analysis procedure with open coding of the content depicted in the videos. To do so, we first transcribed the spoken words in the videos and annotated the videos with a comprehensive description of the scenarios and the behaviours of individuals captured in the footage, including both the recorder and other people featured in the video. Timestamps were added to the transcripts to offer traceability for the analysis process. Additionally, the behaviours of individuals were coded by all three coders using a coding scheme developed and agreed upon by all coders to supplement the scenario analysis. An example video annotation can be found in Table 3.2.

Given the aim of **RQ1** is to identify the real-world encounters documented online that reflect scenarios that require communication between delivery robots and road and sidewalk users, certain eligible videos from the filtering process may not explicitly reflect this need. For example, some videos may only capture a functioning delivery robot without featuring instances that highlight potential communication breakdowns with passersby. To ensure that only videos containing relevant scenarios were included in the scenario identification process, we applied a set of selection criteria. Specifically, we only included scenarios where the lack of communication between the delivery robot and road and sidewalk users could result in confusion, misunderstanding, degraded experience, or potential interaction failure, resulting in

89 videos. The inclusion of scenarios was determined by the lack of communication that disrupted smooth interactions, as directly observed in the video or articulated by individuals depicted. It should be noted that, although selection criteria were implemented to ensure that only videos containing relevant scenarios were included in the scenario identification process, the comments that accompanied these videos were not excluded from the below-mentioned comment analysis. This decision was made to enable an examination of people's attitudes towards the delivery robots within a broader context, rather than limiting the analysis solely to their opinions on communication breakdown situations.

The selected videos were then grouped and summarised into high-level categories based on the robot's behaviours and the interactions that occurred between robots and road and sidewalk users as observed in the video. The behaviours of road and sidewalk users were first directly transcribed from the videos, then systematically coded and categorised based on recurring patterns. The derived categories of the scenarios and the observed behaviours of road and sidewalk users are reported in the results section.

Comment Analysis

We employed a combination of deductive and inductive thematic analysis approaches to analyse the comment data set. The coding process began with a bottom-up approach and was refined through an iterative process to develop a robust coding scheme. In order to incorporate diverse perspectives from researchers in related fields, the data analysis was conducted collaboratively with three coders, including the first author, as well as the third and fourth authors, who are HCI researchers specialising in autonomous vehicle-pedestrian interaction.

The first author conducted a comprehensive examination of the data and selected a representative subset that constituted 10% of the total comments. This subset was subjected to independent coding using an inductive approach by all three coders. The resulting coded data was consolidated into one spreadsheet, and a 1.5-hour meeting was held to review the codes, discuss agreements and disagreements among the coders, and deliberate on the initial themes identified. Following the meeting, the coders collaborated to develop and agree upon an initial coding scheme. The coders then applied a deductive approach to independently code another subset of comments (10%) using the collaboratively developed initial coding scheme. The inter-coder reliability check (Fleiss et al., 2013) was performed on the second subset of 10% comments, which yielded a moderate level of percentage agreement at 0.65.

To further increase the reliability of the coding scheme, we initiated another discussion to iterate over the initial coding scheme. During the second coding discussion meeting, we adhered to a process similar to that of the first meeting, with a specific emphasis on addressing codes with lower agreement rates, in order to ensure a consistent and coherent understanding of the coding scheme among the three coders. We then applied the revised coding scheme to another subset of the 10% comments. The second round of inter-coder reliability checks yielded a high level of inter-coder reliability Fleiss et al., 2013, indicated by a high percentage agreement of 0.85, and a good Krippendorff's alpha Hayes and Krippendorff, 2007 of 0.746. This suggests that the coding process was reliable and consistent and that the codes assigned to the data were valid and accurately reflected the content of the comments, which ensures the credibility of the findings derived from the coded data. Finally, the three coders applied the coding scheme independently to an equal subset of the remaining data. The themes that were identified throughout our comment analysis are presented as part of the results section.

3.6 Video Content Analysis Results

This section presents the results of our video content analysis, which starts with an introduction to the various categories of scenarios where road and sidewalk users require communication from robots to improve their interactions. The related issues that may arise in each situation with the absence of effective communication are also highlighted alongside these categories. We then discuss people's behaviour patterns when encountering robots identified through video content analysis. Our analysis considered various agents of behaviour, including pedestrians, vehicle drivers, cyclists, and other individuals present on sidewalks (e.g., people sitting at cafes). The inclusion of this diverse group aligns with the definition of InCoPs in (Rosenthal-von der Pütten et al., 2020), as they are all stakeholders who may potentially be influenced by the presence of delivery robots.

3.6.1 Extracted Scenarios

To address **RQ1**, a detailed analysis was conducted by annotating, open-coding, and clustering the video content. The analysis identified five typical scenario categories

(a) Obstacle blockage (b) Diverse urban terrains (c) Traffic infrastructure

Fig. 3.1.: Screenshots of example cases of scenario 1: (a) a delivery robot was blocked by a scooter; (b) a delivery robot was unable to climb up a slope; (c) a pedestrian pressed the traffic light bottom for a delivery robot (not captured in the screenshot)

where the lack of communication between the delivery robot and road and sidewalk users could lead to confusion, misunderstanding, degraded experience, or potential interaction failure. In this section, we will present these scenario categories and discuss the issues identified during the analysis process.

Scenario 1: The robot is incapable of performing its task in complex traffic conditions

Despite significant technological advancements that have enhanced delivery robots' mobility, our analysis found that these robots could still face substantial challenges in complex urban traffic environments, impeding their smooth operation. Unpredictable obstacles (as shown in Fig.3.1(a)) and diverse urban terrains, such as road curbs (as depicted in Fig.3.1(b)), can obstruct the path of delivery robots and cause them to become immobilised. Moreover, traffic infrastructures dedicated to human use can present additional challenges for delivery robots. These robots are primarily designed for transportation purposes and lack manipulation functionality, leading to further inefficiencies and delays that require human intervention.

In these scenarios, despite passersby showing care towards the delivery robot, the lack of effective communication from the robot creates uncertainty among people about its status and whether they should offer assistance. This is exemplified by the recorder in Fig.3.1(a) discussing with two other pedestrians whether they should help the robot: *'What happened? Should we help the robot?'*. Furthermore, the absence of communication has the potential to undermine people's trust in the robot. For instance, a comment under a video capturing a stuck robot doubted the capability of the robot, *'Why are we helping them? They're meant to be smart[. . .]'*.

(a) Stopping without obstacles (b) Back-and-forth turning (c) Changing direction

Fig. 3.2.: Screenshots of example cases of scenario 2: (a) a delivery robot came to a halt without obstacles in front of it; (b) a delivery robot repeatedly moved back and forth; (c) a delivery robot stopped beside a driver, turned around to proceed in a different direction

Scenario 2: The robot abruptly stops or redirects, interrupting its smooth operation

The sudden stops or redirections of a delivery robot, which disrupt its consistent operating state, can often cause confusion among nearby road users. As shown in Fig. 3.2(a), where the robot suddenly stopped on a sidewalk with no visible obstacles, the recorder of the video falsely assumed that the robot had detected their presence and stopped, saying. *'It sees me, so it stopped'*. A similar situation occurred in Fig. 3.2(b), where the recorder assumed that the delivery robot's repetitive back-and-forth turning was due to their presence obstructing the robot's path, as reflected by their intention to give way for the robot, *'Hold on, let me get out of your way'*. The uncertainty surrounding the cause of delivery robots' operating interruptions and whether pedestrians are involved can cause them to hesitate or alter their course, resulting in reduced pedestrian efficiency and potential safety hazards in complex urban environments.

Furthermore, unexpected movement interruptions can also lead to assumptions of robot malfunction, which can decrease people's trust. For instance, in Fig.3.2(c), the recorder mistakenly assumed that the robot was *'lost'* when it turned around and headed in a different direction. In a previous study examining people's interactions with service robots in public spaces, unexpected path deviations such as detours were also found to have a negative impact on people's trust in the robot (Nielsen et al., 2022). Therefore, it is essential for delivery robots to provide explanations for changes in their operating state to prevent misunderstandings and avoid disruptions in the traffic flow of other road users.

Scenario 3: The robot needs negotiation with other road and sidewalk users at intersections.

Intersections require effective communication between delivery robots and road and sidewalk users to facilitate successful negotiation among multiple parties. Our video analysis found that the path-planning mechanism of delivery robots often assigns themselves the lowest priority at intersections, leading to extended wait times until there are no vehicles on the road before crossing. However, while this prioritisation may be for safety reasons, the lack of communication with vehicle users can hinder traffic efficiency and lead to frustration among drivers. For example, in Fig. 3.3(a), even though the robot did not exhibit any signs of crossing intention, three out of five drivers came to a full stop and waited for the delivery robot to cross, causing unnecessary delays. In a similar situation, a delivery robot's prolonged wait at the intersection made a driver mistakenly believe that they were obstructing the robot's path, resulting in the driver reversing their vehicle to give way to the robot. Moreover, the absence of effective communication can lead to impatience and frustration among drivers. This was exemplified by a driver's angry shouting towards a stopped robot at a zebra crossing (see Fig. 3.3(b)), where the robot had to stop to give way to another vehicle.

From the pedestrian perspective, even though they are not engaged in the same negotiation process with delivery robots as drivers at intersections, the lack of communication can negatively impact pedestrian mobility, experience, and safety when crossing the street. In some instances, when the delivery robot stopped and waited to cross, pedestrians were observed attempting to guide the robot in various ways, which not only impeded their own crossing but also potentially increased the risk of traffic accidents. Moreover, the delivery robot's waiting behaviour can influence pedestrians' decision to cross. For example, a pedestrian asked a waiting delivery robot *'Are you waiting for me to move?'* (Fig. 3.3(c), instead of crossing the street immediately after the traffic light turned green.

Scenario 4: The robot encounters other road and sidewalk users in close proximity.

When delivery robots navigate urban environments, conflicts with other road and sidewalk users are inevitable, particularly on narrow sidewalks or in bottleneck traffic situations. While delivery robots can typically avoid pedestrians autonomously, the lack of transparency regarding the rules they follow to navigate around people can raise questions about the right of way in such situations. Fig. 3.4(a) illustrates a

(a) Waiting at intersection (b) Stopping when crossing (c) Waiting at the green light

Fig. 3.3.: Screenshots of example cases of Scenario 3: (a) a delivery robot waiting at an uncontrolled intersection; (b) a delivery robot stopping to yield to another vehicle (isn't shown in the screenshot) when crossing and blocked a car; (c) a delivery robot waiting alongside pedestrians

(a) Path conflict (b) Interrupting social activities (c) Close proximity approaching

Fig. 3.4.: Screenshots of example cases of Scenario 4: (a) a delivery robot had path conflicts with an elderly woman in the mobility scooter; (b) a group of people scattered because of the delivery robot; (c) a person expressed shouted due to concerns about being hit by a delivery robot approaching them

scenario where an elderly woman in a mobility scooter had to stop and find a way to navigate around the robot, while another man had to step out onto the driveway. In response to this video, one comment raised the question, *'Can she not give way?'* Furthermore, the lack of communication can also impact the social interactions of groups of pedestrians and their overall comfort in the urban environment. As shown in Fig. 3.4(b), a group of three pedestrians who were chatting together had to scatter as the robot approached, disrupting their social activity by causing them to stop their conversation and temporarily shift their attention from the interpersonal interaction to the robot's movements.

Moreover, as shown in Fig. 3.4(c), pedestrians may be startled by oncoming delivery robots that lack communication regarding their intention to stop. In this scenario, the video recorder was shouting *'stop!'* in terror at the robot approaching them due to concerns about being hit by the robot.

(a) Ignoring police tape (b) Entering marching band (c) Violation of traffic rules

Fig. 3.5.: Screenshots of example cases of Scenario 5: (a) a delivery robot ignored the police tape and entered the crime scene ; (b) a delivery robot entered a marching band (c) a delivery robot violated traffic rules by jaywalking

Scenario 5: The robot does not comply with conventions or regulations.

Our video analysis revealed instances where delivery robots failed to comply with conventions and traffic regulations, potentially due to the challenges posed by complex urban environments and technological imperfections. A typical example of such a scenario is a video showing a delivery robot ignoring police tape and entering a crime scene, as shown in Fig. 3.5(a). A similar case can be seen in Fig. 3.5(b), where a person was trying to direct a robot falsely entering a marching band to leave. These unexpected behaviours led some people to doubt the reliability of the technology, as demonstrated in a comment under the video of Fig. 3.5(a) referring to the robot's actions as a *'tech blunder'*.

Furthermore, it is inevitable that delivery robots may make errors while in operation, and in some cases, even violate traffic regulations. As illustrated in Fig. 3.5(c), the robot was observed jaywalking, and crossing over the motor vehicle lane. These behaviours elicited comments such as *'drives as crazy as a human'* or mention the potential of *'causing a car accident'* under the video, indicating people's safety concerns about the robots. In addition, errors in robot behaviour can lead to a decrease in people's trust in them, as suggested in (Hald et al., 2021). Even though effective communication of the robot's internal state cannot prevent the malfunction from happening, it can still help people better comprehend the situation and plan their own path accordingly, potentially avoiding hazardous outcomes.

3.6.2 Behaviours of road and sidewalk users

In this section, we present six typical behaviour categories summarised from people's interactions with the robot captured in the video. These behaviour categories provide a comprehensive understanding of the dynamics and responses exhibited by individuals when encountering delivery robots, which can offer valuable insights into the design of interactions between robots and other road and sidewalk users.

To account for the potential influence of being recorded, we highlight the number of behaviour instances initiated by the video recorder, as well as the number of protagonists aware of the recording, when reporting the behaviour instance count.

Attention. When encountering the delivery robot, the most frequent behaviour among road and sidewalk users that we observed was slowing down or stopping to gaze[7] at the robot (n=59). In two instances, pedestrians even followed the robot for a brief period of time to observe it more closely. Notably, people's attention was more attracted to scenarios where the robot's movement was interrupted or the robot behaved abnormally, as shown in Fig. 3.6.

Furthermore, our observation indicated that some people showed noticeable interest in the robot's perception channel, such as the camera or sensor. This observation is consistent with the results from our comment analysis result that the robot's perception is one aspect of people's potential information needs. Specifically, five pedestrians approached the front of the delivery robot or got close to its camera to inspect it closely (thereof three were protagonists aware of the recording).

Making Way for the Robot. During encounters with the delivery robot, road and sidewalk users frequently altered their paths (n=20, 6 recorders) or stopped (n=8, 3 recorders) to make way for the robot, particularly when it was in close proximity (as shown in Fig. 3.6). These behaviours suggested that road and sidewalk users were generally respectful and accommodating towards the delivery robot. Notably, some pedestrians even stepped off the sidewalk onto the driveway (n=1) or the lawn (n=2) to allow the robot to pass on narrow sidewalks. It is worth noting that people do not only yield to the oncoming robots as two pedestrians were observed to stop and step aside for a robot coming from behind after noticing its approach.

Apart from pedestrians, vehicle users also exhibited the willingness to yield for the robot (n=5, two recorders) when encountering a stopped delivery robot at an intersection, with three of them stopping completely in front of the robot to make way for it. In three instances, drivers (all recorders) even backed their cars or drove away to maintain a larger distance from the delivery robot, as they believed that their car was detected by the robot and blocking the robot's path.

Assistance. Among the videos in our dataset, there were 14 captured instances where the delivery robot was unable to operate independently due to challenging

[7] The gaze behaviours of the recorders were not counted because all of the videos were captured from a first-person perspective using only the outward-facing cameras of the recorders' smartphones.

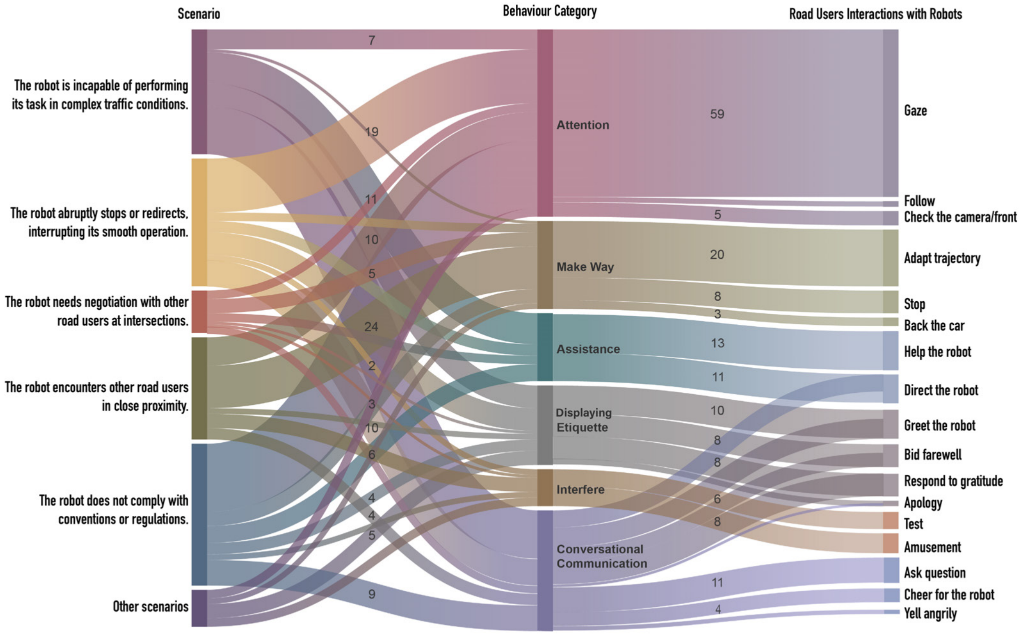

Fig. 3.6.: Alluvial diagram mapping scenarios to road user behaviours. Left column: Different scenario categories, including an *Other scenarios* category for videos that couldn't be categorised due to brief encounters or lack of contextual information.); Middle column: Behaviour category summarised from road user's interactions with the robot; Right column: Road user's interactions with the robot captured in the videos. (It is worth noting that multiple interaction codes can be applied to one single interaction, as behaviours often occur simultaneously or in combination with one another. The left and middle columns may have a higher count than the total, as some behaviours can fall into both the conversational communication category and another category.)

traffic conditions, and in 13 of those cases, the robot received assistance from passing pedestrians. Seven pedestrians physically pushed the delivery robot when it was stuck (thereof 5 were recorders and 2 were protagonists aware of the recording), with one of them even observed escorting the robot with their arms surrounding the robot after it resumed movement. Additionally, six pedestrians assisted the robot in pressing the traffic light button or removing obstacles due to the robot's inability to manipulate traffic infrastructure or move objects (4 recorders). Furthermore, our observation also noted instances of expressed joy and excitement following the provision of assistance help, as evidenced by laughing and changes in their speech tone (n=7, thereof 4 were recorders and 3 were protagonists aware of the recording).

In addition to offering help when the delivery robot encountered difficulty, 11 road and sidewalk users were observed attempting to aid the robot's operation by directing it through verbal or gestural cues when the robot was not moving or had entered a restricted area (e.g. the crime scene as shown in Fig. 3.5(a)) (6 recorders). For instance, in one video where the robot was not moving despite the green traffic light being on, a pedestrian used hand gestures of curling their fingers towards themselves and said *'come on'* to direct the robot to cross the intersection.

Displaying Etiquette. Our observations indicate that some individuals interacted with the delivery robot in a socially conscious manner. The demonstration of social etiquette towards the robot suggests that road and sidewalk users may perceive the robot as a social agent rather than a simple machine, which is consistent with the results of the comment analysis. The social interactions observed include greetings upon encountering the robot (n=10, thereof 8 were recorders and 1 were protagonists aware of the recording), bidding farewell when it left (n=8, thereof 5 were recorders and 1 protagonist aware of the recording), and expressing apologies after obstructing the robot's path (n=2, thereof 1 recorder and 1 protagonist aware of the recording). For example, one pedestrian made a prayer-like hand gesture to express apology towards the robot and gestured an *'after you'* motion to indicate their intention of yielding the way for the robot after blocking its path.

Moreover, one of the delivery robots included in our study was equipped with verbal communication capabilities to express gratitude to pedestrians who provided assistance. In these instances, all eight individuals responded to the robot's gratitude with expressions such as *'you're welcome'* (thereof 6 recorders and 2 protagonists aware of the recording), accompanied by a surprised (n=8) or joyful emotional expression (n=7). This observation suggests that reciprocal social etiquette from a robot could lead to positive social interaction between humans and robots.

Interference. The actions of pedestrians may pose a challenge to the smooth operation of delivery robots. Six pedestrians intentionally tested the robot's operation by intentionally stepping in front of it (thereof 2 records and 2 protagonists aware of the recording). Notably, one of them pretended to tie their shoelaces to mask their intent from the robot instead of standing directly in front of it. Moreover, we observed eight instances of playful behaviours towards the robot, including people playfully chasing it (n=5, including 3 children, 1 recorder), pretending to kick it (n=2), or placing a beverage can on top of it as it passed by (n=1). Notably, no interference from road and sidewalk users was observed in scenarios where robots encountered operational difficulties and are incapable of performing their tasks.

Conversational Communication. Our video content analysis recorded 43 instances of conversational interactions between the delivery robot and video recorders, with 35 initiated by the recorder or protagonists who were aware of the recording, and eight initiated by the robot expressing gratitude as mentioned in the above section.

Among these interactions, 11 were questions posed by the recorder to the robot, such as inquiring about its destination, *'Where are you going?'*, or checking its status, *'Are you lost?'* when the delivery robot exhibited less-than-smooth operation. In such cases, three recorders expressed encouragement for the robot, for instance, by shouting *'You made it!'* when the robot resumed movement from a temporary breakdown. In contrast, one driver expressed frustration by yelling angrily at the robot for blocking their path. Among the observation of conversational interactions between the delivery robot and video recorders, 21 instances of verbal communication were related to social etiquette as introduced above.

3.7 Comment Analysis Results

In this section, we present the results from the thematic analysis of the user-generated comments pertaining to the general public's attitudes toward delivery robots (addressing RQ2). The analysis reveals three broad themes.

The first theme pertains to people's **Perceptions** of delivery robots, including the tendency for people to anthropomorphise the robots, the perception of the robots as social agents, and the overall impression that delivery robots are cute and novel. The second theme concerns the **Acceptance** of delivery robots, including people's attitudes towards the robot presence, their willingness to collaborate with delivery robots, and the factors that influence their acceptance. The third theme covers the **Information** that people would like to know about the delivery robots, such as reasons behind delivery robots' behaviours, as well as information regarding several technical aspects.

3.7.1 Perception

Anthropomorphism The analysis of user-generated comments revealed that people tend to anthropomorphise delivery robots, despite the robots evaluated in the study featuring predominantly mechanical appearances or exhibiting only minimal anthropomorphic traits (e.g., displayed eyes). This was supported by the frequent use of gendered pronouns (n=87, 22.1%[8]) or personification appellations such as *'little guy'* or *'little buddy'* (n=39, 10.0%) when referring to the robots. In contrast, a smaller proportion of people perceived the delivery robots as mere machines (n=20, 5.1%), as demonstrated by their use of robotic appellations when referring

[8]The percentage is calculated in relation to the total count of comments for each sub-category.

Tab. 3.3.: Categories, subcategories, and codes belonging to the theme: **Perception**

Category	Sub-category	Code	Definition
Anthropomorphism	Anthropomorphic referral	Gender pronoun	Using gendered language such as 'he' or 'she' when referring to the robot
		Anthropomorphic appellation	Using anthropomorphic appellation words like 'little guy' or 'little buddy' when referring to the robots
		Robotic appellation	Using robotic appellation words like 'machine' or 'vehicle' when referring to the robots
	Anthropomorphic suggestion	Anthropomorphic suggestion	Suggesting to add anthropomorphic features to the robots
	Mentalisation	Ascribing human thought	Ascribing human thoughts when trying to interpret the robot's behaviour
		Ascribing human trait	Ascribing human traits to the robot such as 'sensitive'
		Ascribing human feelings	Ascribing human-like feelings to the robots such as 'sad'
		Analogy to human behaviours	Making an analogy between the behaviours of robots and that of humans
	Science-fiction influence	Robot domination association	Being reminded of robot domination plot in sci-fi movies when seeing the delivery robot
		Robot characters association	Being reminded of robot characters in sci-fi movies when seeing the delivery robot
Social Agent	Robot to follow social norms	Social communication	Expecting/appreciating the robot to follow social norms when communicating to people
		Social navigation	Expecting/appreciating the robot to follow social norms when navigating around people
		Loss of social interactions	Concerning the loss of social interactions comparing to human delivery
	Human to follow social norms	Social interaction intention	Expressing intentions to engage in social interactions with the robot
		Social etiquette appreciation	Appreciating people to show social etiquette when interacting with the robots
Novelty and Cuteness	Cuteness	Pleasant impression	Considering the robot to be cute or adorable
		Unpleasant impression	Considering the robot to be scary or creepy
	Novelty	Surprise to see the robot	Expressing surprise when seeing the robot
		Being impressed by the robot	Considering the robot to be cool or awesome

to the robot, such as *'box on wheels'*. In addition, five comments suggested adding anthropomorphic features to the robot, such as putting *'googly eyes on them'*.

The tendency to anthropomorphise delivery robots is also reflected by people's attribution of human thoughts (n=73, 18.6%), traits (n=37, 9.4%), and feelings (n=30, 7.6%) to the robots. This process, known as mentalisation in psychology (Gray et al., 2007), has been found to exist in how people interpret robots, as suggested in previous research (Lee et al., 2005; Marchesi et al., 2019). People's interpretation of the robot's behaviour was often guided by their assignment of human-like thoughts to the robot, as demonstrated by one comment assigning thoughts *'Why is it stopped like "I remember you! What do you want human [. . .]"'* to the robot stopping in front of the human in the video. In addition, people also speculated about the robot's characteristics and feelings, as reflected in comments describing the robot as *'polite'* or *'sensitive'*, *'embarrassed'*, *'tired'*, or *'nervous'*. The assignment of the emotion of being *'scared'* (n=5, 1.3%) was used when the robot was observed waiting at an intersection to cross the road or stopped because of human presence. In addition, people often draw analogies between the behaviours of robots and those of humans (n=47, 12.0%). For instance, one comment described a delivery robot stopping at the sidewalk as *'fell asleep'*.

Moreover, our analysis results identified that science fiction films have an impact on the public's perception of delivery robots. A number of comments mentioned their associations with robot domination (n=39, 10.0%) or well-known robot characters, such as *'Wall-E'* (n=16, 4.1%) upon seeing the robots from the video. Although some of these comments may contain a humorous tone, they underscore the pervasive influence of science fiction narratives in media, such as movies, on shaping people's anthropomorphic perceptions. This finding highlights the role that media and cultural representations play in shaping the public's attitudes toward autonomous robot delivery.

Social Agent Our analysis revealed that people tend to perceive delivery robots as social agents, as indicated by their expectation and appreciation of robots' adherence to social norms (n=67, 69.8%). In contrast, only a limited number of comments expressed concerns about the potential decrease in social interactions that could result from relying on robots for delivery instead of humans (n=3, 3.1%), such as '*(losing) small talks with the delivery drivers.'*

Our analysis further highlights the significance of robots' social communication (n=49, 51.0%) abilities in determining their perceived sociability. For instance, one of the delivery robots in our study was equipped with the communication ability to verbally request human assistance and express gratitude through phrases like *'thank you'*, which elicited generally positive reactions from the comments (n=29, 30.2%). Furthermore, politeness is a crucial element of social communication, and people expect robots to display it when seeking human assistance. Some comments criticised the robots for their lack of politeness (n=3, 3.1%), such as one comment stating *'not even a please, it can wait'*. In addition, nonverbal communication modalities such as facial expressions (i.e., screens displaying simple facial expressions) (n=7, 7.3%) and music responses (i.e., playing a short music tune after customers picked up their delivery) (n=4, 4.2%) received positive feedback in 11 (11.5%) comments, which could also contribute to the delivery robot's perceived sociability.

n addition to social communication abilities, people also expect robots to navigate around other road and sidewalk users in a socially polite manner (n=10, 9.6%). For instance, eight comments considered it polite behaviour when the robot stopped or altered its trajectory to give way to other road and sidewalk users. In contrast, in a video where an elderly woman in a mobility scooter was giving way to a robot, two comments argued that the robot should have given way to the woman as a sign of politeness.

The way people intended or appreciated people in the video to interact with delivery robots socially also demonstrated their perception of these robots as social agents. Twenty-six (17.1%) comments expressed people's intentions to engage in social interactions with the delivery robots, including actions such as greeting, *'hug(ging)'*, and *'hold(ing) hands'*. Furthermore, eight comments (8.3%) expressed appreciation for individuals in the video who demonstrated social etiquette when interacting with the robots. In one video, a person's response of *'You are welcome'* to the robot's gratitude elicited a positive reaction from a comment, which stated, *'It made me smile and giggle when it thanked her and she said 'you're welcome'.'*

Cuteness and Novelty Our analysis revealed that people have generally positive impressions of the delivery robot (n=113, 57.7%), with cuteness as a type of attractiveness being the predominant impression that people associate with the robot (n=96, 49.0%). This was indicated by the adjectives used to describe them, such as *'cute'* or *'adorable'*. While this could be related to people's tendency to anthropomorphise robots, three commenters explicitly pointed out that they found the robot to be cute despite its mechanical appearance, e.g., *'WHY ARE THEY SO CUTE?!? They're boxes on wheels and I still have feelings for them!'*. In contrast, unpleasant impressions of robots were relatively rare (n=12, 6.1%). A few comments used terms such as *'scary'* or *'creepy'* to describe the delivery robot.

The novelty of delivery robots is another common impression that they leave on people, as this technology has not yet been widely adopted as a common delivery method in most parts of the world. This is reflected in 73 (37.2%) comments expressing people's surprise upon seeing the delivery robot in the video or asking about it, with phrases like *'What is that [the robot]?'*. In addition, 17 (8.7%) comments used adjectives like *'cool'* or *'awesome'* to express admiration for the robot representing an innovative technology.

3.7.2 Acceptance

Robot Presence The results of our comment analysis suggest a generally positive attitude towards the presence of delivery robots as a service in urban settings (n=119, 68.8%). Specifically, many comments expressed affection for the delivery robot (n=63, 36.4%) and interest in seeing or using the delivery robot (n=43, 24.9%). In addition, 13 (7.5%) comments suggested that the robot represents the *'future'*. In contrast, a relatively small minority of comments expressed a resistant attitude towards accepting delivery robot deployment, with some expressing reluctance to use the service (n=15, 9.2%) or aversions towards the robots (n=4, 2.3%). The negative attitudes towards the presence of robots can also be reflected by people's intentions to perform reckless behaviour towards the robot (n=35, 20.2%), such as *'kick it over'* or *'ram it with my car.'*

Collaboration with Robot In addition to the explicit attitudes expressed towards delivery robots, the acceptance of these robots by the general public can also be inferred from people's opinions on emerging human-robot collaborations (HRC). Most comments (n=204, 98.6%) expressed supportive views towards humans offering help or expressed sympathy for the robots in situations in which they encounter operation difficulties and require human interventions. In contrast, only a minority of respondents (n=3, 1.4%) expressed opposition to offering assistance for delivery robots.

Eighty-eight (42.5%) comments align with the pattern that commenters agree with or express their opinion that people should help robots when they are in need. In several instances, commenters even expressed their intention to assist the robot captured in the video when it encountered operational difficulties (n=15, 7.2%). For example, one comment stated that *'I'd have walked it across the road'* in reference to a robot in the video waiting for a long time to cross an intersection. Furthermore, some comments even criticised the people in the video for not helping the robot or intentionally interfering with it (n=33, 15.9%), as one person stated their angry feeling of being *'heated'* at drivers who didn't yield for the delivery robot.

Moreover, we found that emotional connections and sympathy could be formed with the delivery robot (n=68, 32.9%), as evidenced by people expressing feelings of sadness (n=23, 11.1%) or a desire to *'cry'* for the robot (n=11, 5.3%) when it struggled to complete its tasks. The question of the robot's right of way was also raised, with three comments advocating for the robot to have the same rights as pedestrians, as noted by one comment: *'[. . .] cars are supposed to stop for them. They're considered pedestrians, and it's illegal not to stop at crosswalks.'* These findings could suggest that some people have the tendency to view delivery robots as entities deserving of respect and certain right in public traffic settings.

Factors Influencing Acceptance The comments analysed in our study provide insights into various factors that could impact the acceptance of delivery robot deployments by the general public. A key concern identified in the analysis is the robot's capability to efficiently carry out delivery tasks. While some comments expressed favourable evaluations of the robots' capabilities (n=40, 12.1%) and even preferred them over human delivery (n=5), a larger proportion of comments expressed concerns regarding the robots' capability to complete delivery tasks (n=56, 17.0%) or their delivery efficiency (n=37, 11.2%).

Instead of directly doubting the delivery robots' operational capabilities, 130 comments expressed concerns about the robots' vulnerability in complex or challenging scenarios, particularly regarding their ability to confront deliberate interference by pedestrians (n=97, 29.4%), such as bullying or delivery theft. For example, one person regretfully commented: *'The sad thing is as soon as we saw the robots we knew they were going to get stolen and kicked and messed with.'* In addition to concerns about intentional human interference, challenging road conditions, which could potentially hinder the robots' operation, also emerged as another concern raised in some comments (n=33, 10.0%). For example, one comment expressed their worries about the robot's performance in snowy areas as follows: *'Good luck on our snow-covered sidewalks'*.

Some comments also addressed the potential impacts of delivery robot deployment on traffic (n=25, 7.5%) or society at large (n=42, 12.7%), highlighting the significance of these factors in shaping people's acceptance of delivery robot technology. People's concerns regarding the societal impact of delivery robots were particularly focused on the prospect of job loss resulting from increased automation (n=42, 12.7%). With regard to traffic impacts, despite the smaller size of delivery robots and their consequently reduced likelihood of posing a threat to the safety of other road and sidewalk users, the potential for increased hazards on sidewalks could still result in the reluctance to accept the robots (n=14, 4.2%), as expressed in one

Tab. 3.4.: Categories, subcategories, and codes belonging to the theme: **Information**

Category	Sub-category	Code	Definition
Behaviour Information	Reasons for behaviours	Reasons for behaviours	Questioning or making assumptions of the reasons for the robot behaviours
	Upcoming actions	Upcoming actions	Questioning or making assumptions of the robots upcoming actions
Technical Information	Operation mode	Controlled by human	Assuming the robot is controlled by human operators
		Controlled by AI	Assuming the robot is controlled by AI
		Question	Questioning whether the robot is controlled by human or AI
	Robot perception	Robot perception	Questioning or making assumptions of how the robot perceives the environment
	Robot localisation	Robot localisation	Questioning or making assumptions of how the robot's localisation system (e.g., maps or GPS) works

comment: *'More hazards on the pavements. It's a no from me'*. Besides traffic safety concerns, people also expressed concerns about the possible negative impact of delivery robots on traffic efficiency (n=11, 3.3%), as demonstrated by one comment referring to the video in which a robot blocked the traffic as *'the future of waiting.'*

3.7.3 Information

Behaviour Information Based on the comment analysis, it was found that people request additional information to be communicated by delivery robots, beyond their current features of simple flashing lights or facial expressions. The most frequently discussed topic among the comments was the need to understand the reasons behind the robots' behaviors (n=98, 94.2%). This was evidenced by comments where people attempted to interpret the robots' behaviours (n=85, 81.7%) or questioned why they behaved in a particular way (n=13, 12.5%). For example, one commenter attempted to understand the unexpected path-planning of a delivery robot when it drove off the sidewalk and into the lawn, suggesting that *'Is that his tracks from before? Maybe it's done the route before and it goes in the exact same pattern'.* Compared to the reasons behind the robots' behaviour and actions, the delivery robots' future actions received less attention among commenters (n=6, 9.6%). For instance, one commenter made assumptions that *'after the robot waits 5 minutes it auto returns'* in response to a video depicting a delivery robot stopping on a sidewalk.

Technical Information Technological knowledge related to delivery robots is another common topic of discussion among people. The mode of operation of the robot, specifically whether it is controlled by humans or operated autonomously, is the most frequently discussed aspect (n=62, 72.1%). The majority of the comments hold the belief that the current technology does not allow for fully autonomous operation, so delivery robots are controlled manually by human operators (n=41, 47.7%). Despite the fact that our study included robots with varying levels of autonomy, either fully-autonomous (e.g., Starship robot) or with human operators assisting their operation (e.g., Coco robot), people's assumptions about robot control suggest a limited understanding of robot technology and the necessity of making the operational modes of the delivery robot visible to road and sidewalk users.

Furthermore, specific technical information regarding the delivery robot's perception and localisation was of interest to some commenters (n=24, 28.0%). Comments concerning the robot's sensors (e.g. camera and lidar) and inquiries about whether the robot was *'watching'* revealed their curiosity about how the robot perceives its surroundings (n=17, 19.8%). The localisation system, such as maps and GPS, was another topic of interest in several comments (n=7, 8.1%). For instance, in one video where the delivery robot chose a circuitous path on the pavement instead of a more direct route, one comment assumed that the robot must have *'mapped all pavements separately from streets'*, attempting to justify the robot's behaviour. These comments indicate a need for opening more technical details of delivery robots to other road and sidewalk users, which could enhance public understanding of the robots' capabilities in urban environments, thereby fostering greater trust and acceptance.

3.8 Discussion

Building upon the findings derived from our video and comments analysis, we have identified several design opportunities for interactions between delivery robots and road and sidewalk users. These design opportunities transcend the primary communication purpose of facilitating co-navigation between robots and pedestrians on sidewalks, embracing a broader spectrum of road and sidewalk users and encounter scenarios and recognising the diverse interactions that can occur in different urban environments. Moreover, our investigation has revealed people's additional communication needs for robot transparency information to foster a better comprehension of the robot's behaviour. Additionally, the potential for involving bystanders' intervention in ensuring the robot's operation presents an intriguing avenue for further exploration. In the subsequent sections, we discuss the identified design opportunities and offer design considerations that draw from both the insights derived from our detailed analysis and related HRI literature.

3.8.1 Path Negotiation with Diverse Road and Sidewalk Users

Previous studies have investigated the communication of the robot's motion intentions to humans to facilitate path negotiation, which is similar to the situations observed in the videos where conflicts occur on sidewalks and pedestrians need to navigate a path with delivery robots. These studies have investigated various communication methods, such as using ground-projected arrow graphics (Shrestha et al., 2018; Coovert et al., 2014; Hetherington et al., 2021) to indicate directional intent, and augmented reality through personal devices to convey future trajectory (Yu et al., 2023; Walker et al., 2018). The use of intuitive graphics has been suggested as an effective approach that does not require extensive training (Shrestha et al., 2018; Hetherington et al., 2021) making it an applicable solution to solve path conflict scenarios where delivery robots interact with pedestrians. However, it is important to note that these studies have primarily been conducted in controlled lab settings with adult participants, raising questions about the generalisability of their findings to real-world path negotiation scenarios involving a more diverse demographic. In our study, we observed, for example, the involvement of children or people of different mobility levels. Similarly to Bennett et al. (2021) who documented a case where an individual with mobility issues panicked when blocked by a stopping robot at a crossing, we observed sidewalk users with reduced mobility levels (e.g., the elderly woman in a mobility scooter in Fig. 3.4(a)), having difficulties navigate around the delivery robot. This further underscores the importance of communication for those with limited mobility, taking into account that the ability of these participants to perceive the communication from their physical perspectives and comprehend it may differ from the general population. Therefore, **it is necessary to consider the diverse needs and capabilities of individuals with varying demographic conditions when designing delivery robot communication for path negotiation.**

Although delivery robots primarily operate on sidewalks, they occasionally necessitate moving beyond these pedestrian-only zones. This poses communication challenges among multiple parties, including pedestrians and vehicle users, as intersections serve as dynamic spaces where various road and sidewalk users interact and must navigate their paths through coordinated efforts. From the perspective of a car user attempting to pass through an intersection, delivery robots waiting at uncontrolled zebra crossings could be perceived as pedestrians, given that they leave the sidewalk and cross the pedestrian crossing. Existing research on communication design for autonomous vehicles has predominantly focused on their ability to transmit information to pedestrians, leaving a communication gap between delivery robots and other vehicles at intersections (Rasouli et al., 2018). Pedestrians often signal their intent to cross the road to drivers using various methods, such as eye contact and hand gestures, to ensure safe and efficient negotiation. Delivery robots lack these communication channels, and combined with uncertainty over their right of way, negotiating paths with drivers becomes particularly challenging, leading to decreased intersection efficiency (Rasouli et al., 2018). Our video analysis also revealed instances where drivers mistakenly believed that delivery robots had detected their presence, causing them to reverse to give way (as shown in Fig. 3.3(a). Thus, **the communication between delivery robots and car users at intersections needs to clearly signal the right of way**, which is essential for promoting safe and efficient negotiation, thus avoiding confusion and minimising delays. Additionally, **the communication modalities employed by delivery robots need to consider the accessibility for car users**, due to the physical distance and spatial isolation between them.

Research has shown that pedestrians are heavily influenced by the behaviour of others when making crossing decisions (Faria et al., 2010). For example, when a neighbour starts to cross the street, a person is 1.5–2.5 times more likely to follow them. Our study also identified scenarios where pedestrians' crossings behaviour was influenced by the delivery robot waiting alongside. For example, some pedestrians exhibited hesitation at uncontrolled zebra crossings because of the waiting delivery robot alongside them, even though the pedestrians had the right of way and were safe to cross. In addition to reducing pedestrian crossing efficiency, the influence of delivery robots could also pose potential hazards if it causes pedestrians to make unsafe decisions, such as following the robot and running a red light. Consequently, investigating the impact of delivery robots on pedestrian behaviour becomes imperative. Furthermore, **effective communication is needed for the robot to convey its state of operation at intersections to its surrounding pedestrians, whether it is waiting or moving, to prevent confusion and ambiguity**. However, it is equally important to design communication strategies that do not exert undue influence on pedestrians, thereby avoiding potential risks. Hence, **careful consideration must be given to strike a balance between communicative effectiveness and minimising any leading impact on pedestrian behaviour**. In our study, it was observed that individuals often examine a robot's movements to infer its intentions, highlighting the potential for incorporating such implicit communication strategies into the design of urban robots' communication approaches. To this note, leveraging communication embodied in the robot itself, such as its motion and physical features as suggested by Schött et al. (2023), can be an effective means of conveying the robot's internal state without interfering with the interaction itself.

3.8.2 Additional Information to Support Delivery Robot Operation Transparency

Transparent communication is critical for establishing trust in intelligent systems (Holliday et al., 2016; Schött et al., 2023). In human-robot collaborative contexts, transparency in communication can improve cooperation and teamwork efficiency (Lyons and Havig, 2014; Selkowitz et al., 2017). Our study highlights the need for transparent communication in the context of delivery robots operating in urban shared spaces, even if users may not directly interact with the robot. This is evident from the recurring theme of discussions regarding the behaviours of delivery robots among people's comments. In addition to inquiries about the reason behind the robot's behaviours and actions, some people specifically expressed curiosity about the technical functioning of the robot, such as its operational mode, perception system, and localisation system. This curiosity was further supported by our video content analysis, which revealed pedestrians closely examining the robot's camera and intentionally testing its detection abilities. Furthermore, the comment analysis results indicate that the robot's capabilities play a significant role in the acceptance of this technology. Therefore, providing transparent information beyond conveying motion intent for path negotiation, including clarification of the robot's decision-making and capabilities, is crucial for enhancing public understanding and acceptance of delivery robots.

Considering the complexity of offering such in-depth explanations, Schött et al. (2023) suggested using communication modalities that are inherent to the robot, such as text on the screen and language explanations speech. Nonetheless, it is important to acknowledge that Schött et al. (2023)'s work primarily focuses on scenarios where people have sufficient time for information interpretation, whereas encounters with delivery robots often involve brief, at-a-glance interactions. Therefore, **immediate interpretability is essential for delivery robots to communicate transparent information, making lengthy text or speech explanations unsuitable in such contexts**.

In addition, our study also found that people's informational needs may differ based on the situation: for example, people seem to have a heightened interest in seeking additional information when the delivery robot's behaviour deviates from expected norms or appears faulty. This is evidenced by the increased gaze behaviours towards the robot in those situations (as shown in Fig. 3.6), for example, when the robot is abruptly stopping or violating regulations (as exemplified by Fig. 3.2 and Fig. 3.5). In contrast, we observed that people paid less attention to the robot in situations where it operated smoothly without any noticeable incidents (as shown in

Fig. 3.6). Recent research on robot transparency communication has highlighted the potential issue of information overload when providing pedestrians with too much information that seems unnecessary to them (Yu et al., 2023). Therefore, to address people's informational needs in a more targeted manner and avoid causing information overload, **the design of delivery robot's transparent communication could consider providing additional information upon request, depending on the situation or by detecting people's attention level** (e.g., using gazing detection technology (Li et al., 2016)).

Furthermore, our observations found that people tend to actively engage in conversational communication with the robot when they perceive its behaviour to be confusing. For example, a pedestrian asked a robot that appeared to be lost: *'Do you know where you are going?'*. Recent accelerating progress in large language models (LLM) (Wei et al., 2022), such as ChatGPT [9], provides an opportunity to overcome the communication barriers between humans and robots through the development of interactive verbal communication strategies. Utilising the latest technological advancement for the design of transparent communication for robots, i.e., **using responsive speech to address individuals' inquiries regarding the robot's internal state, could be a feasible solution for providing intuitive communication upon individual requests**. This may not only include robots responding to direct inquiries about their intentions, but also system responses to implicit user input, for example, when recognising patterns in people's gestures and facial expressions. Furthermore, due to the anthropomorphic perceptions of robots as reflected in the thematic analysis of people's comments, the design of robot speech should be carefully considered to align with these perceptions. However, it's crucial to balance conversational interaction with the efficiency of the robot's operations, as engaging in less critical chats with bystanders could potentially delay their primary task, i.e., the delivery of goods.

3.8.3 Bystander Assistance to Support Autonomous Mobile Robot Operation

While extensive research has focused on improving the technical and functional aspects of delivery robots to address the unpredictable urban environment, such as developing more efficient algorithms and robust robotic systems (Lee et al., 2021; Protasov et al., 2021), there are inevitably situations where the robot cannot accomplish its mission without assistance from humans. Our study identified several

[9] `https://openai.com/blog/chatgpt`, *last accessed: April 2023*

common scenarios that are difficult for delivery robots to handle on their own during autonomous operation, such as being blocked by obstacles or unable to manipulate traffic infrastructure specifically designed for humans (as shown in Fig. 3.1). Furthermore, our comment analysis and video observations revealed that people overwhelmingly express sympathy towards delivery robots that appear to be in need of help, and they exhibit positive attitudes towards offering assistance to them. This is evidenced by the predominantly supportive views of human-robot collaboration expressed in the comment analysis, as well as the frequent observations of assistive behaviours from pedestrians. This finding aligns with recent field observations, where researchers found that people voluntarily helped robots that were stuck (Dobrosovestnova et al., 2022) or removed unpredictable obstacles that blocked robots (Weinberg et al., 2023). These findings suggest a design opportunity to leverage bystander assistance as a resource to enhance the efficient operation of delivery robots.

Weinberg et al. (2023) reported in their observation study that in some instances where robots needed assistance, the absence of communication from these robots necessitated that pedestrians had to use context clues to make sense of the situation. Our findings add to this suggesting that individuals hesitate or are unsure how to offer help in the absence of a direct request for assistance from the robot (see Fig. 3.1(a)). To leverage human assistance in robot task operation, several HRI studies have started investigating strategies for robots to request help from people. The conventional approach for robots soliciting help often involves the use of natural language speech as the communication modality (Boos et al., 2022; Cameron et al., 2015; Hüttenrauch and Eklundh, 2006). While effective in indoor settings such as domestic spaces or offices (Srinivasan and Takayama, 2016; Hüttenrauch and Eklundh, 2006), its applicability in noisy public spaces with diverse passersby and multiple languages spoken could be limited. Additionally, Hüttenrauch and Eklundh (2006) suggested that bystanders' willingness to help robots is influenced by the situation and their own state of occupation, which is particularly relevant in urban encounters with delivery robots where people are engaged in various tasks and heading to different locations. Therefore, designing effective help request interactions for delivery robots in such dynamic public spaces poses challenges.

Acknowledging the challenges for robot help requests in dynamic public spaces, Holm et al. (2022) explored the role of expressive movement of robots in effectively eliciting help from individuals. They found that the movement increased people's willingness to help the robot, while static, beeping, and silent robots received much less assistance. The results from our comment analysis also showed that people's sympathy and intentions to help the robot can be evoked simply by implicit expressions that are intrinsic to a non-anthropomorphic robot, such as its movement. For example, people mentioned feeling *'sad'* when seeing the robot's motion of struggling to cross the road and wanted to *'hold its hand to cross the street'*. At the same time, people's tendency to anthropomorphise and infantilise the delivery robots (as evidenced by the comment analysis), e.g., referring to them as a *'cute little guy'*, can also contribute to people's empathetic responses and willingness to provide assistance, as suggested by research in psychology that childlike characteristics can elicit instinctive caring behaviours (Preston, 2013).

In addition to raising people's empathy, expressive movement is also an effective means for robots to convey their incapability and communicate the specific help they require. For instance, employing repetitive back-and-forth movements can be used to signal the need for help in removing obstacles (Kobayashi and Yamada, 2009). Schulz et al. (2021)'s study on robot breakdown situations also suggested that carefully designed expressive movements can make the breakdown situation easier to understand. Therefore, **the design of the delivery robot help request communication could consider using implicit expression channels, such as movement, to communicate their incapability and elicit help from bystanders**.

3.8.4 Limitation and Future Work

We acknowledge that there are some limitations to this study. Firstly, online ethnography of user-generated content may be subject to posting bias. For example, individuals who engage in negative behaviours towards delivery robots may be less likely to post videos or comments about their experiences. This could be a possible explanation for the rare occurrence of robot-bullying behaviour in comparison to previous field studies where robot-bullying has been observed more frequently (Salvini et al., 2010; Babel et al., 2022b). Secondly, it is important not to disregard the potential underlying performative elements that come into play when recorders engage in interactions with the delivery robot, such as increased verbal communication with the robot to enhance the video's attractiveness. This could not only influence our video observation results but also affect the comments responding to the video. Thirdly, the video dataset in our study consisted of content created by and predominantly featuring users of the TikTok platform, which is likely to exhibit demographic biases due to TikTok's user composition (i.e., the majority of TikTok users are aged between 18–34 years in the US). This could result in infrequent observations of child interactions with robots, compared to more frequent observations of those in a recent field study of delivery robots (Weinberg et al., 2023). Despite these limitations, the online ethnography method offers advantages over field observation, including broader geographical and temporal coverage and reduced observer influence. Additionally, the reliability of our method has been validated in a recent field study (Weinberg et al., 2023), as their observations align with some of our findings regarding people's voluntary assistance and verbal communication with the robot.

Furthermore, the limited information available on the deployment history of the delivery robots featured in the videos makes it challenging to differentiate the influence of the novelty effect from that of long-term exposure on people's perceptions and behaviours towards the delivery robots. Future studies may benefit from comparing longitudinal data of real-world deployment of delivery robots to better understand the impact of familiarity on people's interactions with them. Another limitation of this study is the heterogeneity of user-generated content in terms of length and quality. Despite the fact that we adopted strict screening criteria used in similar online ethnography studies (Nielsen et al., 2022; Strait et al., 2017), it is challenging to ensure that the videos we analysed captured the full extent of interactions between the delivery robots and people. Moreover, while this study focuses on identifying real-world scenarios where communication breakdowns happen, we recognise that examining successful interactions—where communication flows smoothly and effectively—represents a significant opportunity for future research. Such investigations could yield valuable insights into design strategies for enhancing the interactions between urban robots and bystanders, paving the way for improved human-robot dynamics in urban settings.

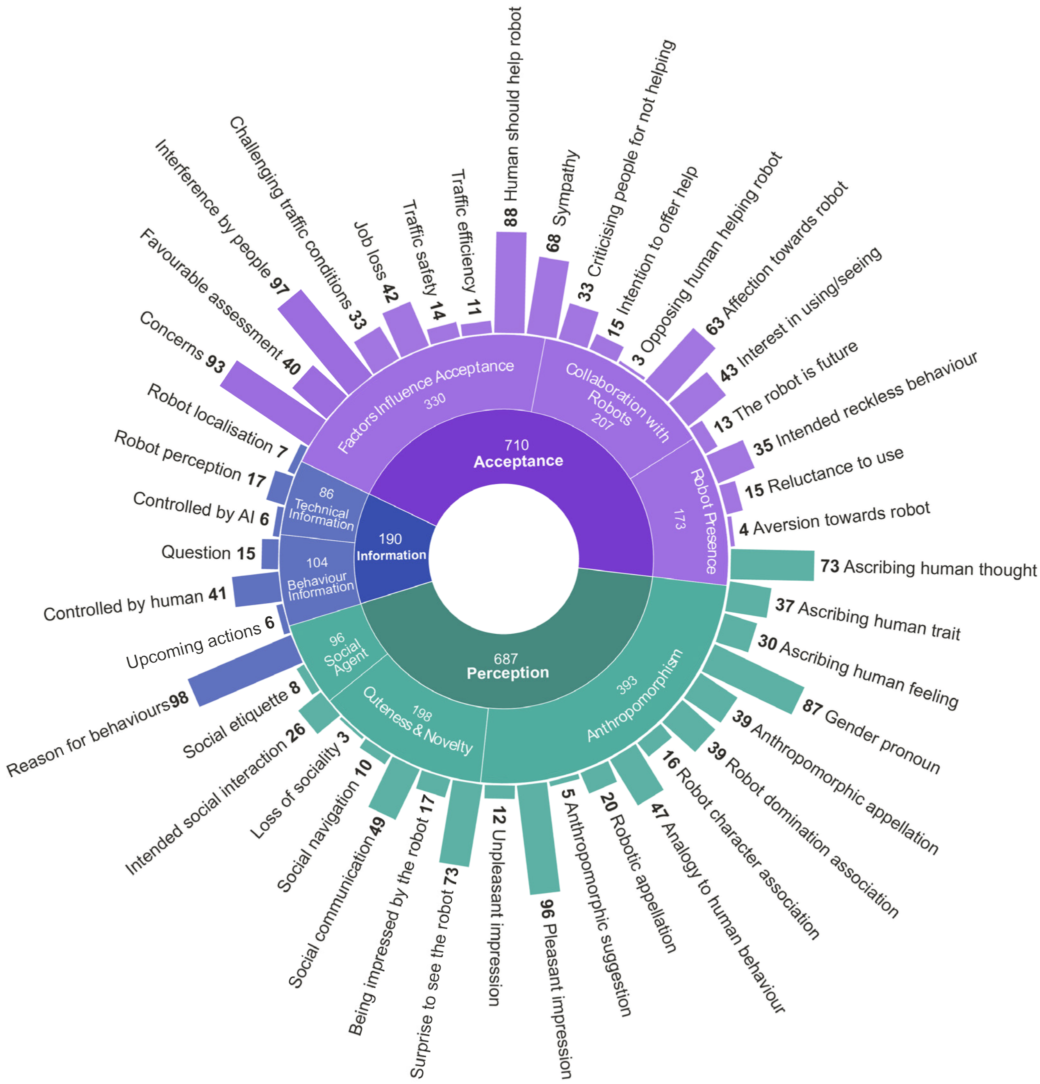

Fig. 3.7.: Themes, categories, and codes identified in the comment analysis, along with the number of comment instances for codes (Sub-categories are not shown in the figure due to the space constraints, and the complete coding scheme can be found in the following tables.)

4 Out of Place Robot in the Wild: Envisioning Urban Robot Contextual Adaptability Challenges Through a Design Probe

4.1 Preamble

Xinyan Yu, Tram Thi Minh Tran, Yiyuan Wang, Kristina Mah, Yidan Cao, Stine S Johansen, Wafa Johal, Maria Luce Lupetti, Megan Rose, Markus Rittenbruch, Rodney G Zsolczay, Marius Hoggenmüller (2024). Out of Place Robot in the Wild: Envisioning Urban Robot Contextual Adaptability Challenges Through a Design Probe. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHIEA '24)*.

This chapter presents findings from a design probe study that explores everyday scenarios in which the presence of urban robots may appear out of place. These findings enrich the design opportunities for casual collaboration identified in Chapter 3, thereby addressing RQ1 *"In what situations does casual collaboration between urban robots and bystanders unfold? What design opportunities are emerging from these situations?"* Furthermore, understanding the issue of urban robots' contextual adaptability contributes insights into designing interaction strategies that facilitate casual collaboration while minimising disruption to urban environments. Thus, this chapter also partially addresses RQ2 *"How can we design interactions that facilitate casual collaboration between bystanders and urban robots?"*

This chapter was originally published as a late-breaking work at the ACM Conference on Human Factors in Computing Systems (CHI) and is available in the ACM proceedings of this conference. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

4.2 Abstract

The increasing deployment of robots in urban spaces calls for design strategies to ensure their adaptation and to mitigate potential disruptions to complex urban contexts. Our research aims to initiate the discussion of contextual adaptability issues of urban robots by exploring everyday scenarios where their presence would appear out of place. We created a design probe for people to carry in their daily lives, facilitating them to envision the robot's presence and capture scenarios where a robot seems to be disruptive. We collected data by distributing the probes among the research team and conducting a city walk activity using the probe at a workshop. This paper presents factors arising from the collected scenarios, encompassing temporal, spatial, cultural, and social dynamics, as well as various stakeholders that robots need to adapt to. These findings provide a blueprint and potential research directions for future research into robot contextual adaptability in urban environments.

4.3 Introduction

As technology advances, robots are moving beyond semi-controlled and routine-shaped settings, such as industrial (Sauppé and Mutlu, 2015) and domestic environments (Schneiders et al., 2021), to undertake tasks in urban environments, thereby becoming an integral part of our cityscapes. These diverse and dynamic environments introduce new challenges for robotic operations, necessitating adaptations to the uncertainties and complexities of real-world interactions with humans. This involves not only the technological capability necessary for efficient task execution but also contextual adaptability that ensures the robot is aware of and appropriately aligned with its socio-contextual settings.

Unlike robots operating in relatively static environments, e.g., interacting with a consistent group of users and operating within a narrow set of dimensions and parameters, adaptability for robots in public urban environments implies a much broader scope. Urban robots encounter a diverse range of individuals encompassing various demographics and engaging in different activities. In addition, a significant portion of these individuals are bystanders who do not intend to interact with the robots (Rosenthal-von der Pütten et al., 2020; Boll et al., 2019), and their existing activities in urban environments could be inadvertently disrupted by the robots' presence. Therefore, beyond merely completing tasks effectively, a robot's ability to recognise and respond to the socio-contextual settings it operates in is crucial (Weinberg et al., 2023). Focusing solely on task execution may render robots out of place and disturb the everyday lives and activities of the urban dwellers surrounding them.

A notable example occurred in September 2022, when a delivery robot crossed into a crime scene, blatantly ignoring the police tape, leaving the surrounding people confused and surprised by the situation. The video[1] capturing the incident went viral on social media, sparking widespread discussion about the potential disruptions caused by such robotic presences in urban environments. This instance is representative of the many real-world scenarios where the presence of robots seems out of place and abrupt, highlighting the need for human-robot interaction (HRI) researchers to study and understand the diverse contexts to which robots must be adeptly adapted. Although it is impossible to foresee the full spectrum of dynamic scenarios that might occur in urban spaces, some of these can be envisioned and reflected upon to anticipate issues of contextual adaptability in the design and development of urban robots.

To envision real-world contexts where robots might be misfits, we developed a design probe, inspired by the cultural probe method by Gaver et al. (1999). Our probe, a pocket-sized photo frame, was designed to elicit imaginative reflections by conceptually integrating robots into everyday urban life and identifying scenarios where the robot's presence could be disruptive or out of place. Data was collected by two means: a) distributing the design probe among an academic workshop organising team and recording their responses (i.e., photographs and reflections) through an online brainstorming board, and b) conducting a city walk (Crivellaro et al., 2015) activity with the same probe and online board during an HRI workshop conducted at the OzCHI'23 conference[2], with all participants subsequently joining as authors of this publication.

In this paper, we report preliminary insights into the desirable contextual adaptability of urban robots based on the analysis of 27 collected entries. Our contributions are two-fold: First, the situational factors and stakeholders necessitating contextual adaptability that emerged from the analysis can serve as a blueprint for fellow researchers to delve deeper into this topic. We further interpret these findings to point out future research directions into robot contextual adaptability in urban environments. Second, our detailed documentation and reflections on the study's methods offer a template for replicating this research in more diverse urban settings.

[1]Available at: `https://www.vice.com/en/article/93adae/food-delivery-robot-casually-drives-under-police-tape-through-active-crime-scene`.

[2]http://www.ozchi.org/2023/

4.4 Method

Understanding the potential misfit of urban robots in everyday urban contexts presents a unique challenge, primarily because these scenarios are often ephemeral and highly dependent on specific contexts and timing. This makes it difficult to anticipate situations where the presence of urban robots would be out of place without actually being in such scenarios. Compounding this challenge is the fact that urban robots are still a relatively novel phenomenon, so their infrequent deployment offers limited opportunities to observe and understand these intricacies in everyday life.

Sumartojo et al. (2021) pointed out the role of imagination in understanding public perceptions and feelings about robots in urban spaces. Adopting an imaginative approach, they created photo collages to visually depict future robots in various spatial contexts and used these images to facilitate discussions about the current and possible roles of robots in public areas, as well as public attitudes towards these robots. Building on the proven effectiveness of using imagination to understand robots in urban contexts, we developed a design probe aimed at eliciting imaginative and reflective responses regarding scenarios in which urban robots might be out of place. We collected data by distributing these probes among our research team and by conducting a city walk activity with the probes during an HRI workshop at OzCHI'23 conference. In this section, we introduce the design probe, along with the data collection and analysis process.

4.4.1 The Design Probe

The cultural probe method, initially introduced by Gaver et al. (1999), utilises various materials such as cameras and diaries for participants to document their daily activities. This approach has been widely adopted in design research as it offers a relatively unobtrusive and lightweight method for gaining insights into how technology can integrate into, or sometimes clash with, specific environments (Wherton et al., 2012; Mattelmäki, 2006). Its aptitude for capturing fragments of daily life and aiding in the collection of autobiographical narratives (Cheon and Su, 2018) aligns well with our research objective to identify everyday scenarios where urban robots potentially misfit. Therefore, we employed this method and developed a design probe to facilitate reflection and develop narratives that reveal how robots might be 'out of place' from everyday life observations.

We developed the design probe as a pocket-sized photo frame (see Fig. 4.1, A), featuring a robot represented in a geometric cube. This basic shape would allow enough space for imagination of potential urban robot form factors and applications. Made from a 1.5 mm screen board using a laser cutter, the frame is portable for participants to incorporate into their daily routines. They could capture various scenarios with the robot image included (see Fig. 4.1, B for an illustration of a person taking a photo with the probe). The probe is accompanied by printed instructions when distributed to participants (see Fig. 4.1, C). We designed this probe to prompt people's reflections through the direct visual representation of robot presence within various scenarios.

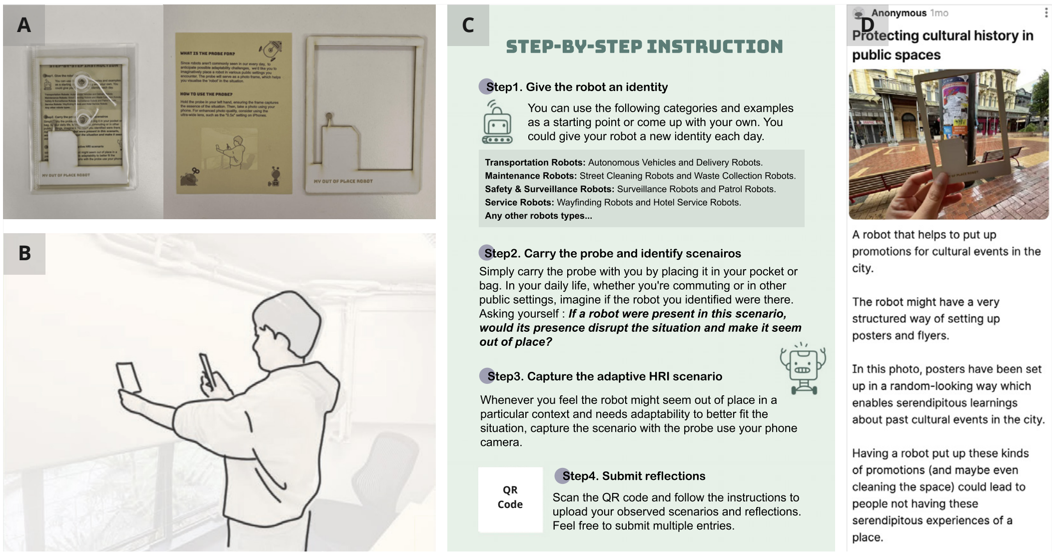

Fig. 4.1.: Design probe and its application: (A) The design probe, (B) Illustration of photo-taking with the probe, (C) Instruction guide, (D) Example post

4.4.2 Framing Imaginative Encounters with Urban Robots

Initial data collection

Data collection commenced with the design probes being distributed to researchers from Design Lab, the University of Sydney, to which four of the authors are affiliated. The research team was instructed to first assign an imaginative identity to the robot (e.g., delivery robot, cleaning robot) and carry the probe with them, envisioning the robot in various everyday life scenarios. In cases when they encountered scenarios where the robot's presence seemed disruptive or out of place, they were asked to capture the scene using their phone camera, framing the scenario with the probe. Afterwards, participants submitted their captured photographs, descriptions of each scenario, and their thoughts on why the robot seemed out of place, to a public content-sharing board, Padlet[3] (see Fig. 4.1, D for an example post). Throughout this stage, we validated the working of the probe and refined the printed instructions.

City walk activity at a workshop

At a workshop held as part of the OzCHI'23 conference in New Zealand, eleven participants, comprising four workshop organisers and seven workshop attendees who later co-authored this paper, engaged in a city walk activity near the workshop venue. This area, located in the central area of Wellington city and characterised by a variety of shops, restaurants, and schools, provided a diverse urban setting for the activity. Each participant was provided with a design probe and paired up to freely explore this area. The activity followed similar procedures to those in the initial data collection stage and utilised the same Padlet board.

In anticipation of rainy weather on the workshop day, we also prepared a virtual city walk using Google Street View[4]. The virtual city walk started with participants choosing a starting point from locations like the center business district, pedestrian zones, and residential areas, as pre-identified by the workshop organisers. Participants then assumed the identity of a robot and navigated freely using the 360-degree imagery function, imagining the presence of their chosen robot in those scenarios. Whenever they encountered a scenario where the urban robot seemed out of place, they documented this discordance by capturing the scene on their screen together with the probe. After thoroughly exploring one location, they moved to the next pre-identified location and repeated the process.

In total, eight participants proceeded with the actual city walk, while three participants opted for the virtual city walk. Both activities lasted approximately one hour. After the city walk, each participant presented the observed scenarios they encountered to all participants. Following this, all participants engaged in a discussion to identify common patterns emerging from the scenarios, and challenges for robots to adapt and integrate smoothly into the urban environment.

[3] `https://padlet.com`
[4] `https://www.google.com/streetview/`

4.4.3 Data Analysis

We received a total of 27 entries from both stages of data collection. To ensure data trustworthiness, we conducted the data analysis with a team consisting of three coders (Church et al., 2019). The analysis process commenced with each coder independently applying open-coding (Corbin and Strauss, 2014) to the collected entries, adhering to an inductive approach. Subsequently, the coders adopted a thematic analysis (Braun and Clarke, 2006) approach to examine the initial codes, searching for common patterns and themes. This phase was followed by a meeting to review and resolve any discrepancies in coding, and to discuss the initial themes identified. Based on the discussion, the first author revised the codes and themes, which are presented in the Results section.

4.5 Results

4.5.1 Robot Types and Roles

The robots featured in the Padlet posts were predominantly ground robots, with three posts mentioning drones. Regarding functionality, many of them were conventional robots with functions that have already been partially implemented in the real world. This includes delivery robots (n=6), way-finding robots (n=5), cleaning robots (n=2), and robots with authoritative roles (n=3) such as surveillance drones and parking fine robots. Five posts depicted more speculative uses of urban robots, such as street entertainment, animal protection, and seed planting. Six posts did not specify the robots' functionalities.

4.5.2 Situational Factors

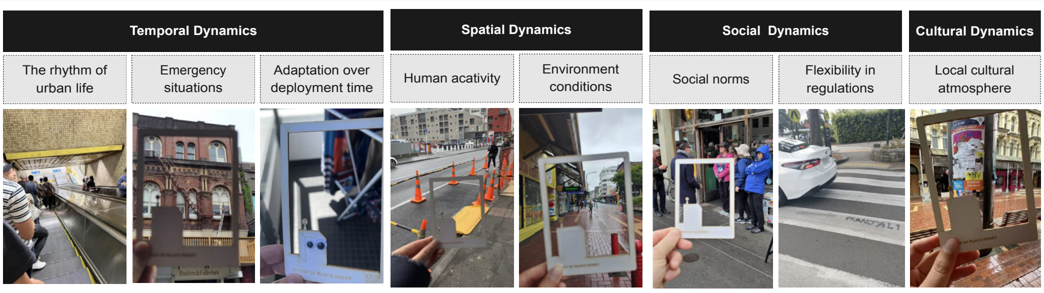

Fig. 4.2.: Situational factors and example scenarios.

Temporal dynamics

Urban contexts are inherently time-sensitive, and a key aspect highlighted in the scenarios is the adaptability of robots to **the rhythm of urban life** and its time-varying contexts. An illustrative example from the Padlet posts mentioned the differing behaviour of people in a train station elevator: the hurried pace during rush hour contrasts with a more relaxed demeanour during weekends. The post raised concerns about the robot being obtrusive if *'fail[ing] to fit into the workday vibe'* by remaining stationary and blocking people urgently ascending the steps.

The temporal aspect extends to robot responsiveness in **emergency situations**, which can alter urban dynamics suddenly and significantly. For example, one post featured an imaginative fire evacuation scenario, where the inability of a robot to react properly could impede the flow of people during evacuation.

Moreover, the robot **adaptation over deployment time** represents another factor for consideration. In the initial stages of introducing a robot into a new environment, a crucial adjustment period is required for the robot to adapt to the novelty effects it has on local inhabitants. Over time, as the robot's presence becomes a normalised and integrated aspect of the everyday environment, a recalibration of its behaviours may be necessary to stay in tune with the evolving dynamics of human-robot interactions.

Spatial Dynamics

The spatial landscape of urban environments is always subject to unpredictable transformations, largely driven by **human activities**. These changes can range from the emergence of construction sites to motorcycles being left in ways that obstruct pathways. During our city walk, a notable instance of this was observed: A previous motorway was transformed into a temporary sidewalk due to construction works blocking the usual pedestrian route. This scenario prompted participants to question how a pavement cleaning robot should respond in such situations: *'Would it seem inappropriate to clean the temporary pedestrian path? Would it seem inappropriate to stop there?'*

The analysis also revealed how human activities and **environmental conditions** intertwine to shape urban landscapes. During the city walk—taking place on a slightly rainy day—we observed an interesting behaviour pattern. As people sought shelter from the rain, they naturally moved under the porches along the street. This resulted in the covered sidewalk becoming crowded, while the exposed side remained empty. This scenario highlighted the risk of *'tripping over the [small] robot'* if the robot fails to adapt to crowded conditions (e.g., by subtly indicating its presence).

Social Dynamics

People rely on **social norms** as a foundation to interact and negotiate with one another. This significance has also long been recognised as an important aspect to consider in designing interactions between humans and robots (Christoph and Jodi, 2004). One illustrative scenario depicted a crowd of people standing outside a coffee shop entrance. The participant imaginatively introduced a delivery robot picking up an order in this context. Their post highlighted the potential of the robot being out of place if it was not aware of social norms, which in this case involves asking people if they are queuing or simply socialising and then taking an appropriate course of action.

In addition, in everyday social interactions, people sometimes prioritise mutual understanding and practicality over strict adherence to formal regulations. One post pointed out the significance of this **flexibility in regulations**, raising intriguing questions about robots' ability to adapt to such fluid social norms. Another post captured a situation where a vehicle had been waiting extensively long at the crossing, yielding to pedestrians. Despite having the right of way, the author of the post chose to step back, signaling the driver to go ahead, in recognition of the driver's extended wait. This instance raised concerns that if a robot were to merely rely on the legal right of way, either proceeding without regard for waiting times or crossing at a consistently slow pace could be perceived as *'inconsiderate'*.

Cultural Dynamics

Compared to the explicit temporal and spatial dynamics, the more subtle and ambient changes in **cultural atmosphere** also play a crucial role in shaping a place. Thus, a robot that fails to adapt to the local cultural characteristics risks being out of place and disrupting the community's vibe. Our city walk activity took place in an area celebrated as the cultural heart of the city, known for its thriving artistic scene. During the walk, one participant noticed a pillar covered with a collage of posters advertising past and upcoming events, and recognised the importance of these posters in expressing the unique character of the place. Their reflection post expressed concerns over robots taking over cultural tasks, potentially diminishing the area's organic charm if they fail to grasp their cultural significance. For instance, a robot organising posters too neatly could undermine the area's distinctive character.

4.5.3 Impacted Stakeholders

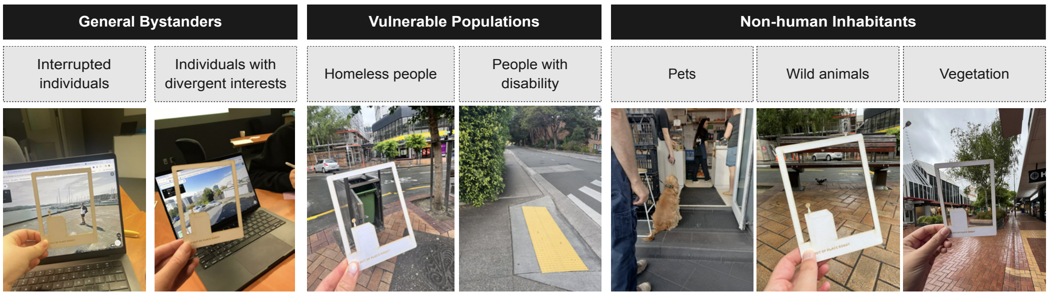

Fig. 4.3.: Impacted stakeholders.

General bystanders

The HRI community has long recognised that robots in public spaces impact not only their direct users but also non-users who encounter them in shared environments without any intention of interaction (Moesgaard et al., 2022; Rosenthal-von der Pütten et al., 2020). Our study captured scenarios where people's activities would be interrupted if the robot, serving other purposes, could not adapt to the situation. One illustrative post highlighted these **interrupted individuals** in the city waterfront area, a place often bustling with tourists and street performances. The author imagined a tour-guiding robot operating in this area and noted that its presence could unintentionally interfere with the surrounding activities and events. In addition, the purpose of the robot sometimes may conflict with the interests of people. An intriguing example of this is an imagined parking fine robot operating in a residential area. The author noted that some people may *'hate'* these robots due to their enforcement role. This situation highlights the necessity for robots to be contextually adaptive to ensure their operational tasks do not lead to alienation or aversion among **individuals with divergent interests**, which is crucial in fostering harmonious human-robot coexistence.

Vulnerable populations

In public spaces, it is natural to extend extra care to **people with disabilities**, such as people with mobility issues or visual impairments. One post illustrated this consideration, describing how people typically make way for individuals in wheelchairs on narrow sidewalks. It emphasised the necessity for robots to adapt similarly, stating: *'If a delivery robot fails to recognise the situation and not making way somehow, it's not very appropriate.'*

Another post discussed the importance of street cleaning robots to recognise **homeless people**. The participant suggested that while performing its task of maintaining urban cleanliness, the robot should be designed to be aware of and accommodate the unique living conditions of this often-forgotten group of vulnerable people.

Non-human inhabitants

Humans are not the only inhabitants of urban environments. Urban spaces are shared with a variety of other non-human living beings. One post depicted a serene morning scenario: people waiting for coffee at a cafe with a well-behaved dog patiently waiting alongside its owner. The author expressed concern about the potential disturbance that a delivery robot might cause for **pets** in the scene. They worried that if a robot were to come close to pick up an order, its proximity to the dogs could make them nervous, leading them to bark and disrupt the quiet of the early morning.

Besides domestic animals, urban environments also host **wild animals** such as birds that are integral to the city's ecosystem, coexisting with human activities. One post collected during the city walk activity put the spotlight on a pigeon, and raised discussion among workshop participants on how robots that primarily serve human needs can *'protect the animal's right to live in the space as well'*.

Vegetation, another crucial component of the urban ecosystem, often receives less attention during the design of technology for public spaces. One post highlighted the potential impact of a delivery drone on tree branches. Noting that the volume of leaves changes with the seasons, it posed the question: *'How much does a drone have to avoid the leaves? What if it is delivering emergency goods?'* The post underscores the necessity for the robot's contextual adaptability to take into account these less-considered living organisms present in the urban environment.

4.6 Discussion

4.6.1 Adapting to Contexts and Being Reciprocal

Our investigation has revealed multiple dimensions shaping the operational contexts of robots in urban environments, encompassing temporal, spatial, cultural, and social factors. The ever-changing urban environments render certain robot behaviours appropriate in some scenarios but not in others, much like the need for humans to adapt to changing urban dynamics. This highlights the limitations of fixed, pre-programmed robot behaviours and underscores the necessity for contextual adaptability. Achieving this adaptability entails both comprehensive design investigations to uncover the specific contextual requirements and the integration of advanced context-aware AI systems (Alegre et al., 2016).

Furthermore, HRI field studies have documented instances where humans accommodate robots in constrained urban spaces, often interrupting their own activities to assist or make way for them (Weinberg et al., 2023; Pelikan et al., 2024). However, this one-sided adaptation suggests an unsustainable imbalance for long-term coexistence. Robots should reciprocate this accommodation, adjusting to the needs of people around them. Our study identifies scenarios necessitating this reciprocal adaptability, ranging from recognising and prioritising the urgent needs of commuters during rush hour to addressing the special requirements of vulnerable populations. This is not only a technical requirement but also a social obligation for ensuring a harmonious and sustainable human-robot coexistence in urban environments. Thus, future research should not only investigate how urban robots can blend into their surroundings but also foster reciprocal adaptability that benefits both parties.

4.6.2 Implicit and Indirect Interruptions

The potential interruptions discovered in our study are not limited to explicit and immediate impacts such as noise or inappropriate disruptions to social activities. They can manifest as subtle influences on the community environment or cultural atmosphere. This becomes evident in cases like the poster-placing robot post (see Fig. 4.2), highlighting the importance of robots being capable of acknowledging and preserving the cultural atmosphere of the community they inhabit. Furthermore, interruptions in urban environments can arise indirectly from entities interacting with robots, not just from the robots themselves. An example is a dog barking due to nervousness caused by a robot in one post (see Fig. 4.3), where the disruption (e.g., noise) is indirectly linked to the robot's presence. Such interruptions are often unforeseen and easily neglected. Therefore, future research should not only address implicit interruptions caused directly by robots but also the implicit impacts and those interruptions that occur in interactions between urban robots and other urban inhabitants.

4.6.3 Unheard Voices from Overlooked Stakeholders

Our investigation resonates with the recent call for HRI scholars to investigate 'who lives and works in the spaces that robots enter' (Pelikan et al., 2024), offering insights into a diverse array of urban inhabitants that are often overlooked. Our findings underscore the necessity of special considerations for vulnerable populations, including children, individuals with disabilities, and homeless people. Expanding further, we advocate for including non-human entities as critical stakeholders in urban robotics. In the broader HCI and interaction design community, the historical focus for a human-centred methodology is being reevaluated in light of emerging research, advocating for inclusive perspectives such as more-than-human (Coulton and Lindley, 2019) and life-centred design (Borthwick et al., 2022; Tomitsch and Baty, 2024). This becomes particularly salient in urban robotics. Urban environments, being ecosystems that host diverse non-human life forms, necessitate considerations that include the broader biological and ecological milieu. Future research should address these overlooked stakeholders by considering their habitation into urban robot design processes.

4.6.4 Reflections on the Design Probe and City Walk Activity

Reflecting on participant feedback, key insights were gained regarding the probe and city walk activity. The physical probe effectively integrated imaginative robot presence into real-world scenarios, with its simple design aiding focus on contextual relevance rather than robot form. Participants noted that scenarios could evolve rapidly, leading to missed photo documentation opportunities. Addressing this, a redesigned probe, either attachable to smartphones or utilising digital AR for photography, would enhance portability and immediate accessibility.

Regarding the city walk activity, while the virtual city walk was suggested to be easy to follow, it has limitations in capturing temporal dynamics and certain environmental effects are more evident in outdoor activities. During the onsite city walk activity, there was an intriguing observation that many participants, who had travelled to the city for a conference and were unfamiliar with the surroundings, approached the activity with a fresh perspective, leading to more imaginative and speculative robot use cases. This observation suggests the potential to enhance the activity by focusing more on envisioning futuristic robot interactions, thereby encouraging innovative and forward-thinking ideas.

This study serves as a pilot test of our probe and city walk activity, and the first stage of data collection. Our future work will build upon these reflections to enhance the probe and activity. We also plan to expand data collection to a larger general population to generate a comprehensive understanding of robot contextual adaptability in urban spaces.

4.6.5 Conclusion

Using a design probe, our exploratory study gains insights into the contextual adaptability of robots in urban environments. By identifying crucial situational factors and the diverse stakeholders that robots must adapt to, we have laid a foundational blueprint and potential research directions for future research. Our study lays the groundwork for the seamless integration of robots into urban life, fostering their harmonious coexistence with urban inhabitants.

Part III

Design Investigation: Emergent Human-Robot Collaboration in Urban Spaces

5 Your Way Or My Way: Improving Human-Robot Co-Navigation Through Robot Intent and Pedestrian Prediction Visualisations

5.1 Preamble

Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2023). Your Way Or My Way: Improving Human-Robot Co-Navigation Through Robot Intent and Pedestrian Prediction Visualisations. In *Proceedings of the ACM CHI Conference on Human-Robot Interaction (HRI'23)*.

This chapter addresses the challenge of path negotiation between pedestrians and urban robots, one of the casual human–robot collaboration scenarios identified in Chapter 3. This chapter presents the design process and evaluation of an augmented reality concept that visualises the robot's navigation intent and the pedestrian's predicted path. A VR lab study was conducted to investigate the impact of our design concept on pedestrians' trust towards robots, sense of agency, user experience, and robot understandability. The design concept was compared against a robot intent–only visualisation and a baseline condition without visualisation.

The design process in this study addresses RQ2 *"How can we design interactions that facilitate casual collaboration between bystanders and urban robots?"* The insights gained from the evaluation study, such as the impact of the visualisation on people's trust and perceptions of robot understandability, as well as people's exploratory reactions, address RQ3: *"How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?"*

This chapter was originally published as a paper at the ACM Conference on Human-Robot Interaction (HRI) and is available in the ACM proceedings of this conference. This chapter was originally published as an article in the ACM Transactions on

Human-Robot Interaction. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

5.2 Abstract

As mobile robots enter shared urban spaces, operating in close proximity to people, this raises new challenges in terms of how these robots communicate with passers-by. Following an iterative process involving expert focus groups (n=8), we designed an augmented reality concept that visualises the robot's navigation intent and the pedestrian's predicted path. To understand the impact of path visualisations on trust, sense of agency, user experience, and robot understandability, we conducted a virtual reality evaluation (n=20). We compared visualising both robot intent and pedestrian path prediction against just visualising robot intent and a baseline without augmentation. The presence of path visualisations resulted in a significant improvement of trust. Triangulation of quantitative and qualitative results further highlights the impact of pedestrian path prediction visualisation on robot understandability as it allows for exploratory interaction.

5.3 Introduction

The safe deployment of mobile service robots requires them to navigate autonomously in close human proximity. This raises the need for socially acceptable robot navigation systems, particularly for shared urban spaces. To enable human-robot co-navigation (Kuderer et al., 2012), i.e. humans and robots safely navigating a shared space, robots have to predict human motion intention and plan their own trajectories correspondingly (Khambhaita and Alami, 2020).

Apart from incorporating socially-aware navigation planning, these robots should also be designed in a way that humans understand how they think and act (Fong et al., 2003). Failure to address this perspective might not only degrade user experience but also affect the operation efficiency of these robots (Bensch et al., 2017). Mobile service robots built in non-anthropomorphic forms (e.g. the majority of delivery robots) are not able to communicate their intention through natural means such as head orientation or gestures (McGinn, 2020). Thus, a growing body of human-robot interaction (HRI) research has investigated the use of additional visual cues, for example, through projections (Han et al., 2022; Chadalavada et al., 2015), LED displays (Kannan et al., 2021), and augmented reality (AR) interfaces (Walker et al., 2018; Gu et al., 2021; Kästner and Lambrecht, 2019; Reardon et al., 2018), to communicate the robot's intent. However, research has also found that a natural, efficient, and safe human-robot interaction requires not only people's understanding of what the robot does or is aiming to do next (i.e. their intent) but also why it acts the way it does (Hellström and Bensch, 2018; Anjomshoae et al., 2019). The HRI community has long recognised the need for understandable robots (Graaf et al., 2018), which spurred a growing body of work designing interfaces providing information behind robot's decision-making process (Wortham et al., 2017; Rotsidis et al., 2019; Selkowitz et al., 2017; Guznov et al., 2020).

Human intention recognition and prediction is a vital determinant of a robot's navigation path planning in shared spaces. While largely investigated from a technological standpoint (Rudenko et al., 2020), to date there have been no studies investigating how communicating this information to pedestrians affects co-navigation and their understanding of the robot's behaviour. Through an iterative process and consolidating feedback collected in expert focus groups (n=8), we developed an AR design concept to visualise pedestrian's predicted path alongside the robot's navigation intent. We then prototyped and compared the concept in a virtual reality (VR) experiment (n=20) against two other conditions, a baseline without visualisation and one only visualising the robot's navigation intent.

The paper makes the following contributions to HRI:

- Proposals for robot intent and pedestrian prediction path visualisations in a shared space.
- Insights about the impact of path visualisations on trust, sense of agency, user experience, and robot understandability in an unplanned human-robot co-navigation encounter.

5.4 Related Work

5.4.1 Mobile Robot Intention Communication

To overcome the shortcomings of robots' non-verbal communication abilities, a substantial body of work has investigated explicit communication approaches to convey a robot's state and motion intention to humans (Shrestha et al., 2018; Fernandez et al., 2018; Watanabe et al., 2015; Baraka et al., 2016; Han et al., 2022). For example, projecting the intended navigation trajectory and occupied space of a forklift robot was found to improve human response in a co-located environment (Chadalavada et al., 2015). Cleaver et al. (2021) further investigated dynamic path visualisation to project a robot's motion intent at varying lengths depending on the complexity of the upcoming path, with results indicating that participants preferred longer path projections.

Apart from using projections onto the environment, other research also explored the use of on-robot communication modalities such as LED light patterns (Tafesse et al., 2018; Kannan et al., 2021) and on-screen displays (Shrestha et al., 2016; Szafir et al., 2015; Kannan et al., 2021). In light of recent advancements in head mounted display (HMD) AR systems, the HRI community further recognised the potential of AR to enable improved communication and interactions between robots and people (Suzuki et al., 2022; Gu et al., 2021; Kästner and Lambrecht, 2019; Reardon et al., 2018). Walker et al. (2018), for example, presented several HMD AR designs to convey an aerial robot's motion intent. Their study showed that the HMD AR designs helped users to better understand the robot's intent, leading to significantly improved task efficiency compared to only relying on physically-embodied orientation cues.

5.4.2 Understandable Robotics

Studies investigating user trust in intelligent system have suggested that understandability is an essential factor determining trust, with the presence of explanations increasing perceived transparency and system understanding (Holliday et al., 2016). The HRI community has also acknowledged the need for understandable robots for a long time, for example, through the organisation of workshops on explainable and trustworthy robots (Graaf et al., 2018; Omeiza et al., 2022). In response to the call for understandable robot-human interaction, Wortham et al. (2017) developed a visualisation system of a robot execution planner (and later deployed it as a mobile AR application (Rotsidis et al., 2019)) to provide real-time graphical visualisations of robot behaviour drives and their priorities. Selkowitz et al. (2017) investigated designing for transparency and understandability in the context of human-robot collaborative teamwork. They compared participants' task performance for four interfaces containing different levels of system transparency information, including goals, reasoning, future projection, and uncertainty. Results indicate that combining the first three types increases subjective trust and facilitates people's comprehension of the robot's actions.

According to the definition of robot understandability by Hellström and Bensch (2018), humans understand a robot when they have sufficient knowledge about the robot's state of mind (SoM). Pedestrian movement intention prediction is a vital part of a mobile service robot's SoM as it determines its navigation planning. However, in current mobile robots, this information is hidden from pedestrians, hindering them from building a more accurate mental model of the robot's navigation and decision-making process.

5.4.3 Pedestrian Intention Prediction

Understanding and predicting human motion has become a critical ability for intelligent systems to co-exist and interact with humans, especially in application domains such as autonomous vehicles and service robots (Rudenko et al., 2020). State-of-the-art deep learning models consider different aspects, including gestures (Ratsamee et al., 2015), group behaviour (Li et al., 2020), and context (Kooij et al., 2014), to improve the accuracy of motion prediction. While there is continuing technological advancement in pedestrian intention recognition and prediction, to the best of our knowledge, there is no research on how to make this information transparent to pedestrians in co-navigation scenarios with mobile robots. However, studies from related contexts and domains offer a foundation for our research. For example, in the context of driver vehicle interaction, Kim et al. (2016) presented a head-up display (HUD) AR system using a shadow overlay to indicate where pedestrians are predicted to cross. Their evaluation proved the effectiveness of visualising pedestrian motion intention to help drivers build an accurate time-distance judgement of the vehicle and other moving obstacles. In the context of highly automated driving, Colley et al. (2020a) displayed recognised pedestrian intention to passengers inside the vehicle and compared two visualisation modalities, tablet display and HUD AR. Their study results demonstrated the effectiveness of visualising pedestrian intention in improving users' trust and a preference for AR-based visualisations.

5.4.4 Summary

To sum up, there is an extensive body of work in HRI on mobile robot intention communication and a few explorations to make internal decision-making processes visible to users. However, a majority of work focused on indoor settings (e.g. shared floor space (Chadalavada et al., 2015), corridors (Shrestha et al., 2018)) and addressed anticipated human-robot collaboration scenarios, in which people and robots operate jointly as a team (Walker et al., 2018). As a consequence, previous work in this domain mainly evaluated the effects of robots' additional information cues on task performance (Han et al., 2022; Chadalavada et al., 2015; Cleaver et al., 2021; Dragan et al., 2015) or perceived communication efficiency (Kannan et al., 2021; Fernandez et al., 2018), while rarely paying attention to how they affect trust during occasional and unplanned encounters in public settings. Responding to the call of improving understanding of autonomous systems for casual bystanders (Boll et al., 2019), our work extends the information the mobile robot communicates to pedestrians beyond intent and raw sensor data to some of the internal processes influencing its decision-making and broaden the empirical investigation of such visualisations in regards to the impact on people's trust and sense of agency (SoA).

5.5 Design Process

Research through Design (RtD) (Zimmerman et al., 2007) is a well-established research methodology that is known for its capability to facilitate design explorations and generate new knowledge throughout the process. In recent years, RtD has also been applied in HRI (Luria et al., 2019; Luria et al., 2021). We chose RtD to guide the design of our path prediction visualisation as it has been found to support reevaluating underlying assumptions and reframing design problems in exploratory research (Zimmerman et al., 2022). In this section, we outline the assumptions that we made based on related studies, describe the methods used as part of the design process, and discuss how the findings led to a reframing of our research questions and informed the proposed path prediction visualisation.

5.5.1 Methods

We used an iterative approach to developing design proposals. The initial design proposals were based on previous findings in related work and involved the first author developing and refining proposals based on feedback from the other two authors. Given the complexity and domain-specificity of our design investigation, we invited experts of various relevant backgrounds as our focus group participants in order to effectively identify key issues. We first sought feedback through a focus group with four participants, including one robotic expert (E1), one HRI researcher (E2), and two interaction designers (E3, E4). Reflecting on the findings, we reframed the purpose of the path prediction visualisation to support participants in developing a mental model of how robots make navigation decisions. We revised the design proposals accordingly and conducted a second expert focus group with four participants, including two HCI researchers (E5, E6), one HCI/HRI researcher (E7), and one interaction designer (E8). A different set of participants was recruited for the second focus group in order to reduce potential effects of preconceptions or biases, while at the same time collecting feedback from a larger sample size. Based on the findings from both focus groups, we then identified the design parameters for the path visualisation and formulated the research questions for the subsequent evaluation study.

5.5.2 Initial Design Proposals

Previous findings suggest that the presence of mobile robots in shared spaces influences pedestrians' navigation behaviours in several ways. First, it makes some pedestrians deviate from their original trajectory to keep an unnecessarily large distance (Vassallo et al., 2018; Kümmerle et al., 2015). Second, pedestrians might walk in a reckless way (Prédhumeau et al., 2023) or even perform risky behaviours towards robots (Madigan et al., 2019), causing failures in robot navigation (Salvini et al., 2010). Studies investigating human-robot teamwork suggested that providing robot transparency information can improve people's performance in a collaborative task (Guznov et al., 2020; Lakhmani et al., 2019). In addition, previous findings further suggest that human motion prediction is an essential factor influencing socially acceptable robot navigation (Khambhaita and Alami, 2020). We thus hypothesised that if pedestrians could see their upcoming trajectories as predicted by the robot, they could follow this hint and cooperate, improving the pedestrian's experience as well as the robot's operating efficiency. Drawing on findings from in-vehicle path prediction visualisations (Colley et al., 2020a), we also hypothesised that visualising the pedestrian's predicted path could positively influence pedestrians' trust towards robots.

Building on previous work that suggests AR as a strong candidate to enhance human-robot interactions (Walker et al., 2018; Suzuki et al., 2022), we decided on an initial design concept of using HMD AR to visualise the predicted path visualisation. As all data is sensed centralised by the robot unit, every pedestrian wearing an HMD receives path prediction information of all detected pedestrians, even of those who don't wear a gear themselves.

To evaluate these preliminary assumptions, we probed the design idea in a focus group. We used images and video mock-ups as representations of the initial concept (see Figure 5.1, left) to foster discussions with participants on different aspects,

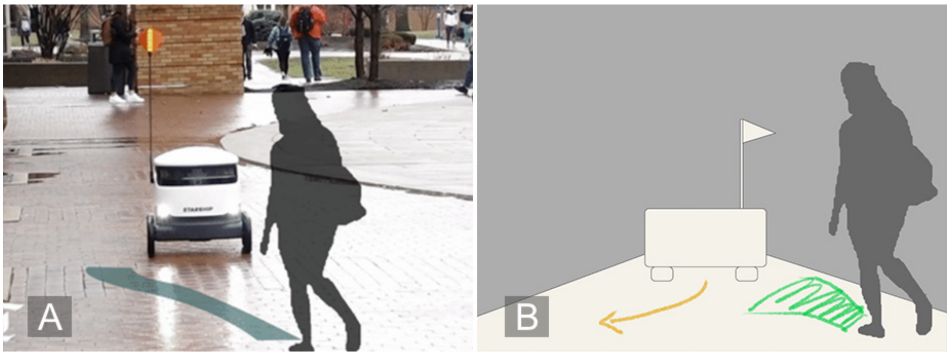

Fig. 5.1.: Representations of design concepts: initial concept showing the pedestrian's predicted path (A) and refined concept featuring both the pedestrian's predicted path and robot intent (B).

including their willingness to comply with the predicted path, subjective feelings and trust. We also discussed additional feedback they would like to receive from the robot, e.g. to encourage them to follow the predicted path.

Unexpectedly, we found that participants' interpretations of the predicted path visualisation and reactions to it vastly varied depending on their prior knowledge of robotics. The robotics expert (E1) instantly understood the predicted path visualisation and expressed a willingness to follow it. In contrast, the other three participants (E2-4) generally had inaccurate interpretations of the visualisation, assuming it was the *'recommended path'* or a *'command'* from the robot. This misinterpretation reduced participants' willingness to follow the path, refusing to follow *'what a robot tells me to do'*. In terms of trust, all participants agreed that the acquisition of more knowledge behind the robot's decision-making could improve their trust. However, the visualisation did not immediately increase trust for E2-4 who failed to understand the visualisation when first exposed to it. After being introduced to path prediction, they expressed their interest in testing the prediction, indicating their trust may be enhanced after assessing how it functions. Furthermore, apart from our original investigations, we also discovered a potentially negative impact visualising the predicted path could have on people's sense of agency as E2-4 expressed their feeling of *'being controlled'* by the robot.

5.5.3 Design Refinements

Based on the insights from the first focus group, we made adaptations to our initial design concept. Unlike in the case of visualising pedestrian intent recognition for passengers inside AVs (Colley et al., 2020a), we found that additional information is needed for pedestrians in co-navigation scenarios to make use of the information.

This might be due to the fact that the origin and addressee of the path prediction information are identical. Furthermore, the first focus group evaluation showed that a more accurate mental model of the robot's path planning is needed to make the predicted path visualisation understandable to general pedestrians. To cater for this, we created several variations based on our initial design, such as adding the robot's navigation intent (see Figure 5.1, right) and indicating the robot's field of view (as suggested in (Lynn, 2021)) through outgoing radar waves and virtual eye designs. In the second focus group, we investigated the effectiveness of such additional information cues to contextualise the path prediction visualisation, thus facilitating people's understanding. We used images and video mock-ups of our adapted design variations to facilitate discussion of how additional information could improve the initial design proposal.

The predicted path visualisation – manifesting the 'reason' for the robot's behaviour – was more understandable for participants when accompanied by its 'result' – the robot's intended path. All participants agreed that the robot's intended path was the most crucial information to contextualise the predicted path visualisation as it also showed how their behaviour would influence the robot's path planning. Three participants further indicated that they would be more willing to follow the path when they could see the robot's navigation path. The findings confirmed the importance of indicating the robot's field of view. All four participants preferred eyes as a metaphor for the robot's perception, serving as an association that the predicted path is the calculation result of the data collected by the robot's sensor. Based on these findings, we further refined our design decisions as follows:

- Visualising the predicted path using a green-coloured area with arrows; transparency gradually decreases from the pedestrian's position onward to indicate that prediction accuracy decreases with distance.
- Visualising the robot's intended path through yellow arrows.
- Visualising other pedestrians' predicted paths within robot detecting areas in cyan (to support understanding of the robot's path planning through interactions between the robot and other pedestrians).
- Overlaying the robot's front with virtual eyes to gaze at pedestrians when their predicted path starts to influence the robot's path planning.

The colours chosen for the visualisations follow the standards of road sign design in the Manual on Uniform Traffic Control Devices (MUTCD) published by the US Department of Transportation (MUTCD, 2002). We use yellow for the robot's intended path to convey warning of potential interference and green for the predicted path visualisation to convey permitted traffic movements or directional guidance. The paths of other pedestrians are visualised using the same graphics but with cyan as a more neutral colour, allowing pedestrians to distinguish between their paths and those of others.

5.5.4 Research Questions

We revisited our initial assumptions and underlying research questions in light of several insights gained from the findings across both focus groups. First, the findings validate the potential of predicted path visualisation in enhancing pedestrian trust. Second, findings demonstrate an inaccurate understanding of the path prediction when displayed in isolation. Third, feedback from the robotic expert (E1) challenged that pedestrian compliance with the predicted path has little effect on the operational efficiency of the robot itself because of the high algorithm update frequency. We therefore turned to investigate how the visualisation of robot intent and pedestrian's predicted path can improve understanding of the robot's navigation. Furthermore, participant's assessment that the predicted path visualisation may negatively affect their agency in co-navigation scenarios motivated us to further examine the impact on sense of agency (Gallagher, 2012) in addition to the earlier identified factors of trust and user experience.

We thus formulated the following research questions to guide the evaluation of our path visualisation concept:

- To what extent, if any, does the visualisation of robot intent and pedestrian path prediction enhance people's understanding of robot navigation?
- How will the robot intent and pedestrian path prediction visualisation affect people on (1) trust, (2) sense of agency, and (3) user experience?

5.6 Evaluation in Virtual Reality

Given that our design concept includes both the robot's intent and the pedestrian's predicted path, a comparison to a conventional robot communication method that only conveys intent would yield clear insights into how visualising the robot's decision-making process affects pedestrians. To evaluate the effects of visualising the robot's intent and the pedestrian's predicted path, we conducted a within-subject study with three experimental conditions (see Figure 5.2): a robot without external communication visualisation (*baseline*), a robot with AR visualisation of its intended navigation path (*intent*), a robot with AR visualisation of both the robot's intended path and the pedestrian's upcoming path predicted by the robot (*intent* + *predict*).

We decided on a VR simulation that allows participants to experience co-navigation with a delivery robot in a shared space. VR simulations have been widely used for prototyping and evaluating interactions with autonomous vehicles (Colley et al., 2020a; Colley et al., 2021; Colley et al., 2022; Gerber et al., 2019). They lower development costs and potential risk to participants while at the same time offering high ecological validity and interaction fidelity, for example, in comparison to video-based simulations (Hoggenmüller et al., 2021b).

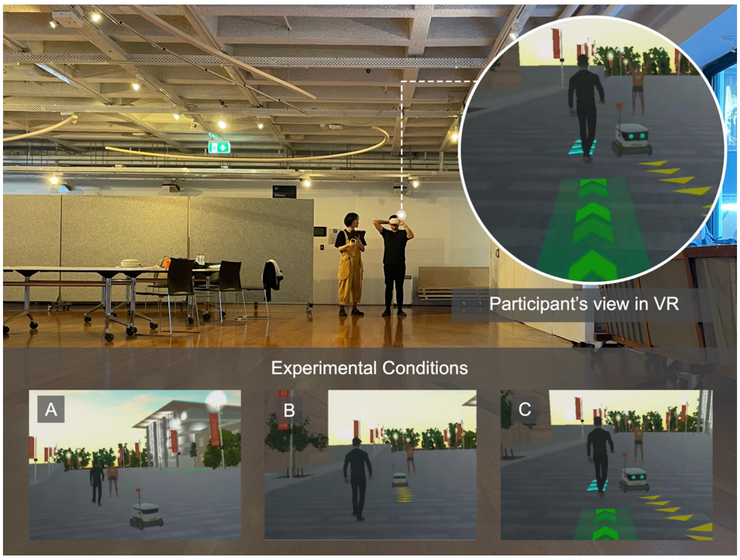

Fig. 5.2.: Study setup, the participant's perspective in VR, and experimental conditions: baseline (A), visualising the robot's intent (B), and visualising the robot's intent and the pedestrian's predicted path (C).

5.6.1 Study Apparatus and Implementation

We implemented the VR simulation using Unity3D[1] and deployed it to an HMD headset, the Oculus Quest 2 providing a fully untethered 6DOF experience[2]. The experiment was conducted in a 12x5-meter open floor space, where participants were able to physically walk through the simulated scenarios.

We chose a 3D model of our university's campus avenue as the surrounding environment, since it represented a typical example of a shared space. Given that our

[1]https://unity.com/
[2]https://www.oculus.com/quest-2/

participants were recruited from the university community, they were likely familiar with the environment, making it easier to relate to such a speculative scenario (Gerber et al., 2019; Hoggenmüller et al., 2021b). For the mobile robot, we used a 3D model of the delivery robot Starship, obtained from the modeling platform Sketch Fab. The robot simulated the essential path planning functions.

We predicted participants' upcoming trajectory using exponential smoothing model (Gardner Jr, 1985), which is a widely used statistical model in time series forecasting. We took eight points to predict the estimated subsequent coordinate and repeated the process until the following eight points were calculated. The predicted points were used to render the real-time visualisation in the virtual environment. As the technical implementation was not the focus of our study, we decided on a simplified path prediction model. Furthermore, a state-of-the-art deep learning algorithm would have required extensive computing power not provided by standalone HMD hardware. It is worth mentioning, however, that the feedback provided by four participants during pilot testing validated that our approach offered a realistic sense of their upcoming path being predicted.

5.6.2 Participants

We recruited 20 participants aged 21 to 37 (M = 27.1, SD = 4.43). Eight of them self-identified as male, 12 as female. Participants were recruited from our university's mailing lists, flyers and social networks. All participants voluntarily took part in the experiment and initial contact had to be made by them, following the study protocol approved by our university's human research ethics committee. Of our participants, seven had previously encountered robots in public spaces and five had seen cleaning robots in domestic spaces.

5.6.3 Procedure

After participants arrived at the study site, they were first given a brief introduction to the study background and procedure. They were then asked to sign a consent form, followed by a demographic questionnaire that obtained their basic information, including age group, gender, occupation, nationality, and previous experience with AR/VR and mobile robots. Following this, we briefly introduced the VR headset and its basic operations, and notified participants that the HMD VR was used to simulate the experience of seeing the visualisation with a wearable AR device. Prior to experiencing the conditions, each participant went through a familiarisation session in which they practised walking in the virtual environment. This also allowed us to ensure that participants did not experience motion sickness and were willing to proceed with the study.

Each participant experienced three experimental conditions in different orders (using balanced latin square design to minimise carryover effects). To ensure that there was sufficient time for participants to get familiar with the visualisations, each participant experienced four different scenarios per experimental condition. In doing so, we also aimed to cater for different co-navigation situations that could occur in a shared space. The direction in which participants and the robot would move relative to each other (e.g., facing each other or passing in front of the robot) and the placement of other virtual pedestrians differed in each scenario. Virtual pedestrians were added to simulate a more realistic shared space experience, and to help participants to understand the visualisation based on how the robot responded to the predicted path of the virtual pedestrians.

To motivate participants to walk through the virtual scene (thus, encountering the robot while walking), we placed a virtual avatar that waved to the participant at the 'destination point'. Prior to the experiment, we briefed participants that this was a 'friend' that they were planning to meet with. After participants walked virtually (and physically) to the destination, they could enter the subsequent scenario by confirming a user interface overlay via the hand controller. Before continuing with the following scenario, the experimenter ensured that the participants would turn around by 180 degrees, thus making optimal use of the limited physical space and avoiding potential collisions. After each condition, participants removed the headset and were asked to fill out standardised questionnaires on trust, sense of agency, and user experience. After participants completed all three conditions, we conducted a post-study semi-structured interview to gain in-depth insights into their experiences. The whole study took approximately 45 minutes.

5.6.4 Data Collection

We collected both quantitative and qualitative data through questionnaires, observations and interviews, following a mix-methods approach (Creswell, 2014).

To assess participants' trust towards the robot, we used the Trust in Automation Scale (Jian et al., 2000) with all items corresponding to 7-point Likert scales. This is a standardised questionnaire that is designed to measure people's trust in autonomous systems and has been widely used in HRI (Xie et al., 2020; Xu et al., 2018; Wright et al., 2019). In considering the feedback obtained from the focus groups (i.e. that the predicted path visualisation might affect pedestrians' autonomy), we measured the participant's sense of agency using the Sense of Agency Scale (SoAS) (Tapal et al., 2017) on a 7-point Likert scale. It measures people's perceived control over their own mind, body, and the environment and has been previously used to assess perceived agency when interacting with social robots (Horstmann and Krämer, 2022). To measure participants' user experience, we used the short version of the widely adopted User Experience Questionnaire (UEQ-S) (Schrepp et al., 2017) on a 7-stage scale from -3 to +3.

We took observation notes of participants' reactions towards the robot by observing their physical behaviour and monitoring interactions in the virtual environment (streamed in real-time to the experimenter's iPad). We additionally screen-recorded the VR interactions for later verification of observation notes and to contextualise participants' statements from the interviews. Through semi-structured post-study interviews, we asked questions about their preference between the three experienced conditions, their perceived trust towards the robot, their interpretation of the AR visualisations, and their perceived sense of agency.

5.6.5 Data Analysis

Questionnaires: We first calculated Cronbach's alpha to assess the internal reliability of all scales used. Internal reliability was excellent for the *trust* subscale (α=0.945) and good for *distrust* (α=0.812). For the SoAS, internal reliability was good for *positive agency* (α=0.883), but poor for *negative agency* (α=0.627). Following advice on Cronbach's alpha in (Tavakol and Dennick, 2011), we removed items with a correlation lower than 0.25 (item 3, item 6), which made the internal reliability for the remaining items acceptable (α=0.717). For the UEQ-S questionnaire, item reliability was good for *pragmatic quality* (α=0.889) and excellent for *hedonic quality* (α=0.916).

We conducted and report on descriptive and inferential analysis of questionnaire data. As data was non-parametric, we used Friedman test to determine statistically significant differences. We further performed pairwise comparisons with Bonferroni corrections in case of significant differences. We considered an effect significant if the p-value was less than 0.05.

Interviews: All interviews were transcribed manually by the first author. The interview data was analysed following an inductive thematic analysis approach (Braun and Clarke, 2006).

We first coded all quotes, sorted initial codes into sub-themes, and grouped them into final themes. Observation notes were used to supplement the analysis of the interview data.

5.7 Results

5.7.1 Trust

Trust Scale

Following descriptive data analysis (see Figure 5.3), participants' trust was highest in *intent + predict*, while their distrust was lowest in *intent*. Friedman's ANOVA showed significant differences in both trust ($\chi^2(3)$=22.605, p<0.001) and distrust ($\chi^2(3)$=15.041, p<0.001) subscales. Post-hoc tests revealed that both *intent* ($p = 0.002$) and *intent + predict* ($p < 0.001$) received significantly higher trust ratings compared to *baseline*. Conversely, participants' distrust ratings in *baseline* was significantly higher than in *intent* ($p = 0.006$) and *intent + predict* ($p = 0.003$). There were no significant differences between *intent* and *intent + predict* in either trust and distrust subscales.

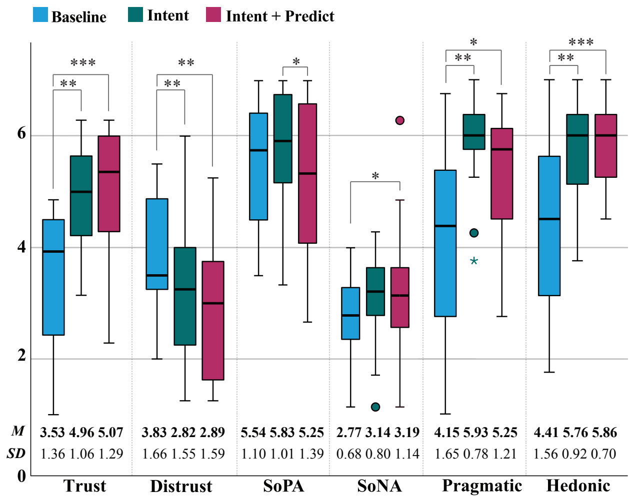

Fig. 5.3.: Results of (1) Trust Scale, (2) SoA Scale, and (3) UEQ-S (scale adjusted to increase comparability). *: p < .05, **: p < .01, ***: p < .001

Qualitative Feedback on Trust

Even though the quantitative data did not show a significant improvement of trust in *intent + predict* compared to *intent*, during the interviews, over half of the participants (n=14) indicated that *intent + predict* improved their trust towards the robot. Below we discuss the reasons for participants' improved trust discovered in the post-study interviews.

Firstly, this provided participants with a confirmation that they had been *'seen'* by the robot (n=7). In contrast, participants (n=5) indicated that their insecurity in *baseline* was mainly due to the uncertainty of whether the robot had detected them, e.g. *'I feel unsafe as you don't even know if the robot sees you or not'* (P6). Secondly, the dynamic response of the robot's intended path according to the predicted path made participants understand that the robot was actively calculating its paths to avoid collisions with pedestrians, which made some participants feel *'safer'* when navigating around the robot (n=9). When asked about the experience in *baseline*, some participants expressed scepticism about the robot's intelligence, suggesting that the robot *'looks silly'* (n=3), and even felt that the robot was just a *'toy'* (P16). In contrast, the robot in *intent + predict* was perceived by almost half of the participants (n=9) as *'more intelligent'* and 'smarter', which also contributed to their trust. Two participants even suspected that what they encountered in the three experimental conditions was *'not the same robot'*. None of the participants proactively mentioned the robot's eyes during the interview. When asked about robot eyes, more than half of them said that they did not notice them, with only four participants stating that the eyes made the robot more like a living creature. Thus, the robot's gaze could slightly contribute to the perceived intelligence.

Although *intent+predict* provided additional motivating factors for trust and improved perceived trust for more than half of the participants, some participants (n=3) indicated a preference for *intent* rather than *intent+predict*: they pointed out a decrease in trust caused by potentially inaccurate prediction results of the pedestrian's upcoming trajectory - an issue that they did not find for only visualising the robot's navigation intent. Another participant, P17, also raised trust issues in relation to data security, which only surfaced for them through making the path prediction visible: *'What if it will send my data to somewhere I don't know?'*. Diverse perspectives and the variety of factors at play influencing participant's trust may account for the non-statistically significant difference between *intent* and *intent+predict*.

5.7.2 Sense of Agency

Sense of Agency Scale

Descriptive data analysis of the SoA scale (see Figure 5.3) showed that sense of positive agency (SoPA) was rated highest in *intent*, while unexpectedly sense of negative agency (SoNA) was rated lowest in *baseline*. This contradicting result might be due to the only moderate correlation between the two subscales (Tapal et al., 2017). *intent + predict* received the lowest ratings in SoPA and highest in SoNA, indicating a negative impact on participants' sense of agency. The Friedman's ANOVA showed significant differences in both the SoPA ($\chi^2(3)$=7.690, p=0.021) and SoNA ($\chi^2(3)$=8.247, p=0.016) subscales. Post-hoc tests revealed a significant difference between *intent* and *intent + predict* in SoPA subscale ($p = 0.027$), while no significant differences were found between *baseline* and the other two conditions. The SoNA rating in *intent + predict* was significantly higher than in *baseline* ($p = 0.043$). No significant difference was found between *intent* and the other two conditions.

Qualitative Feedback on SoA

Even though in the interviews only four participants explicitly expressed their feeling of *'being controlled'*, the quantitative data revealed the negative impact of predicted path visualisation on participants' SoA. Below we discuss interview data relating to SoA in order to gain further insight into which factors contributed to this assessment.

Most participants indicated a high degree of autonomy during the co-navigation task with the robot, e.g. determining their path *'based on own judgment'* (P11) instead of simply *'follow[ing] where the robot was telling to go'* (P15). Nonetheless, the predicted path visualisation still influenced participants' behaviour for two main reasons: Firstly, the concern that not following the predicted path would malfunction the robot made some participants feel their actions were *'restricted'* (P6, P11). As P6 stated: *'I think if I did something weird, for example, turning right or left out of sudden, I felt like the machine might not detect it.'* Secondly, some participants indicated that they followed the path *'unconsciously'* (n=6), which might lead to a decrease in their sense of agency.

5.7.3 User Experience

UEQ-S Questionnaire

Descriptive data analysis (see Figure 5.3) of UEQ ratings shows that *intent* and *intent + predict* were the highest in pragmatic quality and hedonic quality, respectively. In contrast, *baseline* remained the lowest in both subscales. Friedman's ANOVA showed significant differences in both pragmatic ($\chi^2(3)$=15.53, p<0.001) and hedonic quality ($\chi^2(3)$=20.94, p<0.001). Post-hoc tests revealed that both *intent* ($p = 0.002$) and *intent + predict* ($p = 0.010$) received significantly higher ratings for pragmatic quality than the *baseline*. At the same time, the hedonic ratings were also significantly higher for *intent* ($p = 0.002$) and *intent + predict* ($p < 0.001$) in comparison to the *baseline* condition. Yet, no statistically significant difference was found between *intent* and *intent + predict* for both subscales.

Qualitative Feedback on User Experience

Being asked which condition participants would prefer from a user experience point of view, eleven participants opted for the *intent*, while eight participants preferred the *intent + predict*. Only one participant preferred the *baseline* condition, which most of the other participants considered as *'unsafe'* (n=6) and *'obstructive'* (P19). Through the thematic analysis of interview data, we identified a number of underlying reasons for these assessments, outlined below.

Despite the majority of participants (n=13) being in favour of additional information, which would help them to understand the robot's navigation decision-making, the opinions on the necessity of the displayed information in a scenario that is only occasionally encountered varied. Some participants (n=8) suggested that the predicted path visualisation provided *'convenience'* (n=3) as it made the upcoming co-navigation with the robot *'predictable'* (P15) and *'so it's more clear that I don't have to give way to [the robot]'* (P10). Others stated that explanatory information such as the predicted path visualisation would add to their cognitive load and could be *'distracting'* (n=3) or even *'confusing'* (n=2). This was further underpinned by our observations, indicating that some participants (n=7) were more hesitant in *intent + predict*, i.e. walking slower than in the other two conditions or even stopping after a few steps (n=3).

Interview data showed that the predicted path visualisation raised participants' *'interest'* (n=16), describing their experience in the *intent + predict* condition as ‘*interesting*’ (n=6), ‘*cool*’ (n=3) and ‘*fun*’ (n=2). This again is in line with our observations that revealed how participants increasingly engaged in exploratory interactions with the robot in the *predicted path* condition (n=11). Post-study, nine participants explained their exploratory behaviours with a feeling of ‘*curiosity*’ invoked by the predicted path visualisation, which even made the interaction with the robot feel like ‘*play[ing] a game*’ (n=2). AR, on the other hand, was regarded as an unfamiliar application for most participants (n=12), which also contributed to the perceived novelty of the experience.

5.7.4 Robot Understandability

When asked about their interpretation of the predicted path visualisation, most participants (n=17) stated that it improved their understanding of how the robot ‘*thinks*’. Three of them further indicated that they did not fully understand the robot when first seeing it but started to do so after seeing the effect that their actions had on the robot's behaviour: ‘*At first, I didn't realise that my path was linked to [the robot's] path. The moment I realised this was when I walked past it and I saw that its path had changed and veered off.*’ (P18). Some participants indicated that their understanding of how the robot worked was improved after actively testing it (n=6): ‘*I tried to block it and to see its reaction [. . .], so I got it.*’ (P9).

The predicted path visualisation also caused inaccurate interpretations of the robot for a few participants (n=3). For example, P7 incorrectly interpreted the path prediction visualisation as ‘mind-reading’: ‘*I was thinking to turn right (without actually performing the turning action), but [the robot] didn't notice that*’. This misinterpretation of the robot's prediction capabilities caused suspicion in P7, considering the robot as ‘*not reliable*’.

5.8 Discussion

In this section we discuss the findings from across the design process and the evaluation study's quantitative and qualitative data sources and contrast them to prior work. Within each subsection we describe recommendations for designing robot explanatory visualisation and opportunities for future work.

5.8.1 Reflections on Visualisation Preferences

Expanding study results on the effect of robots' motion intent on improving collaborative task efficiency (Walker et al., 2018; Cleaver et al., 2021; Dragan et al., 2015), our results show that communicating such information can also enhance people's trust towards robots in unplanned encounters (e.g., co-navigation scenarios in public spaces). Although no significant difference of trust was discovered between the two visualisations, qualitative data revealed positive aspects that explanatory information might have on people's trust, such as making the robot's capability of safely navigating explicit and enhancing people's perception of the robot as an intelligent agent. A robot's perceived intelligence was found to correlate with its animacy (Bartneck et al., 2009a), while our study indicates the possibility of increasing non-humanoid robots' perceived intelligence by providing explanatory information. Yet, it is worth noting that the theme of perceived intelligence emerged from qualitative interview data. Thus, a systematic evaluation using scale measures for perceived intelligence (Bartneck et al., 2009b) would be able to shed further light on these findings.

Despite the additional incentives for trust and the improvement of robot understandability, interview data showed comparable participant preferences between *intent* (n=11) and *intent+predict* (n=8), which are likely linked to the evenly matched user experience scores, and the higher SoA score in *intent*. While the information conveyed by *intent + predict* strengthened participant's understanding of the robot's behaviour, intent was effective enough for a bit less than one-third of participants (n=6) as co-navigation guidance during casual encounters, which indicates different informational needs across individuals. In addition, people's needs for explanations may also vary depending on the situational context, as suggested by two participants that the predicted path visualisation was especially helpful in a scenario where they could not decide how to give way to prevent the robot from bumping into a virtual pedestrian. In comparison, it was *'unnecessary'* in scenarios where the co-navigation went smoothly. Building on these findings, future work could therefore investigate how to balance the benefits of conveying prediction information versus causing information overload, for example, through alternative information visualisation techniques.

5.8.2 The Relation Between Explainability and Sense of Agency

During the focus groups, we identified people's willingness to dominate interactions with robots in co-navigation situations and the potential influence of exploratory information on people's SoA (Moore, 2016). Previous work in HRI has investigated the impact of the robot's presence on people's SoA, suggesting a decrease in SoA in human-robot joint action (Grynszpan et al., 2019). Thus, researchers are looking for solutions to restore SoA for operators of autonomous intelligent systems (Pagliari et al., 2022; Sankaran et al., 2020). Our study results show that people's SoA could potentially increase when the robot communicates its intention, which is in line with Pagliari et al. (2022), who argue that communicating an AI system's intention to its operators can improve their self-agency. Although pedestrians are not direct operators of mobile service robots, communicating the robot's motion intention still improves their confidence in co-navigating around robots, thus positively influencing their user experience during interactions.

In contrast, our study results also showed that visualising path prediction reduces pedestrians' SoA and increases hesitancy in co-navigation decisions. The interviews revealed that this negative impact on SoA is partly because participants may unconsciously take the predicted path visualisation as an instruction, causing the feeling of being 'controlled' by the robot. These findings combined have important implications for the design of transparent and explainable autonomous physical systems: while some information regarding a robot's behaviour and action may increase people's SoA, in some cases information can even have a reverse effect. Future research should therefore investigate what explanatory information to provide, through which message and communication strategy, and how to visualise, thereby considering the situational context of both robot and addressee.

5.8.3 Interactive Approach to Establishing Understanding

From the VR observation results, we found that the predicted path visualisation raises participants' interest in engaging in exploratory interaction with mobile robots. These interactions can support the understandability of the mobile robot's navigation behaviours: users can test and explore how the robot responds to their changing behaviour on the spot, which in turn helps them understand the capability and reliability of the robot's navigation. This finding echoes recent calls within the community to engage users in 'open-ended' explorations of an AI system's behaviour through interactive explanations (Abdul et al., 2018; Suzuki et al., 2022). Currently, research investigating robot understandability in human-robot collaboration settings often provides interfaces with text-heavy descriptions (e.g. by highlighting labels in a static decision tree (Wortham et al., 2017)). As such interfaces require a longer and more focused attention span, they are less suited for public spaces, in which people are likely to be in a rush and encounter robots as casual bystanders in an unplanned manner (Naiseh et al., 2021). Our findings thus suggest that highly visual and dynamic explanatory cues such as path prediction visualisations can foster exploratory engagements that better fit casual encounters with robots.

Nevertheless, as our study showed, exploratory interactions stimulated by explanations could also increase the likelihood of passers-by interfering with service robots and thus negatively impacting their operational efficiency. In previous research, it has also been observed that due to curiosity, people disturb the robots' task performance (Pernis, 2022) and even treat robots aggressively, causing damage (Salvini et al., 2010). Future research could explore solutions to counterbalance these issues. At the same time, as suggested by some of our participants, predicted path visualisation may be more suitable for educational purposes in order to train the general public about the capabilities and behaviour of robotics.

5.8.4 Limitation

First, the findings of our evaluation study drew on the experiences of a small number of mostly university students and young professionals. Although we anticipate comparable outcomes, a larger representative sample would be beneficial, particularly in resolving some borderline quantitative results. Second, the ecological validity of this work is limited by the use of a VR simulation. The virtual environment could not entirely recreate the complex multi-sensory experiences in the real world. The novelty of the VR experience and the fact that the robot in VR does not threaten participants' safety may also increase the likelihood of engaging in exploratory and risky behaviours. Third, because exposure to such internal information of a robot was a novel experience for all participants, causing *'unreal'* feelings for some (n=4), results may differ after long-term deployment and as familiarity increases, which need to be further validated in future studies.

5.9 Conclusion

In this paper, we described the design process and evaluation study of an AR predicted path visualisation to promote robots' understandability for pedestrians in an unplanned encounter scenario. The evaluation study results showed that both the *intent* and *intent + predict* visualisations can significantly improve pedestrian's trust and user experience, with *intent + predict* additionally reinforcing people's understanding of how such systems work by engaging them in exploratory interactions, thus providing extra incentives for further trust improvement. We also discovered a positive influence of robot intention communication on people's sense of agency and that adding the pedestrian's predicted path visualisation had a negative effect, which is an issue raised during focus groups. Participants' divergent informational requirements highlighted a need for flexible, customised and context-dependent explanatory visualisation. Our study unfolds the discussion of 'opening the black box' by helping people develop a mental model of how mobile robots operate through dynamic path visualisations. Future studies could more systematically study what other information about a robot's navigation decision-making process could benefit its understandability.

6 From Agent Autonomy to Casual Collaboration: A Design Investigation on Help-Seeking Urban Robots

6.1 Preamble

Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2024). From Agent Autonomy to Casual Collaboration: A Design Investigation on Help-Seeking Urban Robots. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*.

This chapter bridges real-world needs and challenges in casual collaboration between urban robots and bystanders with design concepts that facilitate such collaboration through a bodystorming-based design investigation. The help-seeking scenarios investigated in the study were identified in Chapter 3. This chapter addresses RQ2 *"How can we design interactions that facilitate casual collaboration between bystanders and urban robots?"*. The study yields insights into factors that influence bystander assistance towards urban robots, as well as bystanders' expectations regarding the qualities of robot help-seeking strategies. The design considerations derived from this chapter—such as leveraging playfulness as an incentive for bystander engagement—inform the subsequent design concepts in Chapter 7, Chapter 8, and Chapter 9.

This chapter was originally published as a paper at the ACM Conference on Human Factors in Computing Systems (CHI) and is available in the ACM proceedings of this conference. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

6.2 Abstract

As intelligent agents transition from controlled to uncontrolled environments, they face challenges that sometimes exceed their operational capabilities. In many scenarios, they rely on assistance from bystanders to overcome those challenges. Using robots that get stuck in urban settings as an example, we investigate how agents can prompt bystanders into providing assistance. We conducted four focus group sessions with 17 participants that involved bodystorming, where participants assumed the role of robots and bystander pedestrians in role-playing activities. Generating insights from both assumed robot and bystander perspectives, we were able to identify potential non-verbal help-seeking strategies (i.e., addressing bystanders, cueing intentions, and displaying emotions) and factors shaping the assistive behaviours of bystanders. Drawing on these findings, we offer design considerations for help-seeking urban robots and other agents operating in uncontrolled environments to foster casual collaboration, encompass expressiveness, align with agent social categories, and curate appropriate incentives.

6.3 Introduction

Contemporary Human-Computer Interaction (HCI) is still predominantly anchored in a human-centric paradigm (Shneiderman and Plaisant, 2010; Norman, 2013) that anticipates intelligent agents to perform tasks autonomously via algorithm-driven solutions, thus providing assistance and services to humans. Rooted in this prevalent narrative of technological efficiency, there exists both widespread expectation (Sheridan, 2016) and active technological pursuit (LeCun et al., 2015) for agents to operate with heightened independence and expanding autonomy (Lyons et al., 2021).

However, as agents transition from controlled environments to public spaces tailored to human needs (Salvini, 2018; Rosenthal-von der Pütten et al., 2020; Tomitsch, 2018), they inevitably encounter situations beyond their programmed capabilities. This inherent limitation is challenging to eliminate in the foreseeable future (Veloso, 2018). Consequently, in the realm of human-agent collaboration, while the primary focus has long been on developing agents that intelligently serve humans, there is now growing attention toward agents that actively seek human assistance when needed (Cila, 2022). This trend is evident in both exploratory projects of human-dependent robots (Weiss et al., 2010; Smith and Zeller, 2017; Kinzer, 2009), and also emerging perspectives from the design research community. These studies increasingly define human-agent interaction less in terms of an agent's standalone capabilities and more about the symbiotic relationship between humans and agents (Lupetti et al., 2019; Kuijer and Giaccardi, 2018; Marenko and Van Allen, 2016).

The increasingly pervasive deployment of urban robots has provided real-life contexts to these perspectives that once seemed speculative. Recent field studies capturing the operational challenges faced by urban service robots, coupled with the unsolicited aid they receive from passersby (Dobrosovestnova et al., 2022; Weinberg et al., 2023), underscore the value of bystander assistance. In traditional human-agent collaboration settings, where both parties typically commit to a joint activity and shared objectives, straightforward verbal cues may suffice for robots to seek assistance from collaborators (Srinivasan and Takayama, 2016; Rosenthal et al., 2012). However, public spaces introduce a slew of additional challenges for robots and agents soliciting assistance. These range from resolving misaligned objectives to taking into account the diverse backgrounds of bystanders and their different availability given the array of activities they might be engaging in. Therefore, in these settings, leveraging bystander assistance is not merely a functional imperative but may become a foundational element for the harmonious integration of robots into societal contexts. The emergence of such casual collaborations between agents and humans calls for designers to explore effective strategies for agents to seek human assistance (Cila, 2022).

In light of these considerations, our work investigates *how agents can elicit help from bystanders when they encounter operational challenges*. To ground our investigation in real-life scenarios, we derived situations from a previously conducted online ethnography study, where delivery robots encountered operational difficulties as evidenced in user-generated videos. Drawing inspiration from pioneering works that utilise embodied methods to enliven design exploration (Gemeinboeck and Saunders, 2017; Dörrenbächer et al., 2020; Gemeinboeck and Saunders, 2023; Gemeinboeck and Saunders, 2018), we conducted four bodystorming focus group sessions with 17 participants. For these sessions, we applied a mystery-game style to bodystorming (Abtahi et al., 2021), where the robot player was assigned a hidden task of soliciting assistance to resume operation. Participants actively re-enacted the scenarios, embodying the roles of either robots or pedestrians, and sought to solve this challenge by fostering casual collaboration among them.

Through in-situ understanding and bodily exploration, our work contributes to HCI by: (1) offering a preliminary understanding of factors influencing bystander assistance to agents in public spaces; (2) generating design considerations for agents seeking help from bystanders in these settings. Our research adopts a Research through Design (RtD) (Zimmerman et al., 2007; Luria et al., 2019; Prochner and Godin, 2022; Godin and Zahedi, 2014) approach, which adheres to its own validity criteria, emphasising recoverability that ensures the process is transparent and can be critically evaluated by other researchers (Zimmerman et al., 2007). Consequently, we meticulously documented the implementation of embodied design methods and shared insights on how these methods promote our design exploration.

6.4 Related Work

In our work, we investigate casual collaboration between humans and agents, exemplified through urban robots encountering obstacles and seeking assistance from bystanders. We draw on and contribute to: (1) human-agent collaboration, (2) robot help-seeking strategies, and (3) service robots in urban spaces.

6.4.1 Human-agent collaboration

With the advancements in artificial intelligence, interactive products and systems have transitioned from performing programmed tasks under human supervision, to achieving higher level of autonomy, emphasising self-governance, adaptability, and collaborative interactions with humans (Lyons et al., 2021; Xu, 2020; Cila et al., 2017). These artefacts – commonly referred to as agents – include smart devices, robots, virtual agents, and voice-activated personal assistants. To support the shift towards more efficient human-agent collaboration (Bellamy et al., 2017), the evolving dynamics between humans and agents have become a topic of enduring interest across different HCI communities (Momose et al., 2023; Johnson and Vera, 2019; Cila, 2022; Bradshaw et al., 2017). Often inspired by theories from the social sciences and drawing on human-human interaction and behaviour studies, researchers developed frameworks to inform the design of interfaces and agent behaviour for human-agent teamwork settings. For example, Johnson et al. (2014) introduced the coactive design approach, which is centred on the idea of mutual interdependence, underlining the essential principles of mutual observability, predictability, and directability for effective collaboration between humans and agents. Cila (2022) drew insights from the Shared Cooperative Activity (SCA) framework, a model of human-human collaboration introduced by Bratman (1992). By reviewing its core tenet, the study underscored the importance of mutual support and pointed towards the need to investigate effective means for agents to request help during collaborations.

6.4.2 Robot help-seeking strategies

In human-robot collaboration (HRC) settings, research has explored various strategies to equip robots with the capability to seek assistance from human collaborators to complete a joint task. These methods include verbal cues (Knepper et al., 2015; Srinivasan and Takayama, 2016; Budde et al., 2018) and non-verbal signals such as movement (Kwon et al., 2018), light, and sound (Cha and Matarić, 2016). Due to the shared objectives and mutual understanding between humans and robots in these human-robot teaming contexts, such methods often enable efficient communication and prompt assistive behaviours from human collaborators.

In contrast to human-robot team settings where both parties share a mutual goal and have knowledge of the task, the dynamics of help-seeking become more complicated when robots interact with unassociated individuals such as casual bystanders. Contextual factors like specific task scenarios and the bystander's current activity (Hüttenrauch and Eklundh, 2006), combined with individual factors, such as the bystander's trust towards and perceived competence of robots (Cameron et al., 2015), collectively shape assistive behaviour. Despite the misaligned task objectives and the added complexities of various contextual factors, there is a noticeable absence of tailored design strategies or investigations for robot help-seeking from bystanders. Both academic research (Wullschleger and Brega, 2002; Rosenthal et al., 2012; Kerstin et al., 2014; Liang et al., 2023) and commercially deployed robots (Boos et al., 2022) predominantly resort to verbal help-seeking strategies from bystanders in public environments. While validated to be efficient in human-robot teaming scenarios, their effectiveness in casual collaborations between robots and bystanders in public urban environments may be compromised by factors like cultural and linguistic differences, cognitive overload, and ambient noise and distortion. To our knowledge, the only study that expanded exploration on communication modalities is (Holm et al., 2022). They investigated the interplay of movement with auditory cues such as beeps and synthesised speech. Notably, their findings suggest that non-verbal expressions may elicit higher empathy from bystanders compared to verbal requests.

6.4.3 Service robots in urban spaces

Transcending initial static and semi-controlled configurations (e.g., laboratories (Salter et al., 2004),factories (Hägele et al., 2016), domestic environments (Chatterjee et al., 2021)), robots have expanded their presence to public urban spaces, reshaping our cities. Urban robots serve various sectors, including transportation, infrastructure maintenance, cleaning, and surveillance (Salvini, 2018).

Despite technological advancements, questions remain about how well these robots can operate in urban environments that are populated by and designed for humans (Plank et al., 2022). Given the diverse infrastructure and unpredictability of urban settings, it's challenging to fully anticipate the feasibility of different operational scenarios for robots during their development process. A vivid demonstration of this challenge emerged from several viral videos on social media in 2021, depicting delivery robots struggling in Estonia's heavy snowfall (Palmipuu, 2021). Beyond the evident operational difficulties, a fascinating aspect of these incidents was the spontaneous assistance offered by passersby to these commercially deployed machines to help them resume moving (Dobrosovestnova et al., 2022). The prosocial behaviour from bystanders was also observed in a recent field observation study (Weinberg et al., 2023), where pedestrians voluntarily assisted immobilised robots by removing obstacles. These observations underscore the potential of leveraging bystander assistance to enhance the operation of urban robots. This aligns not only with exploratory projects involving human-dependent robots (Weiss et al., 2010; Smith and Zeller, 2017; Kinzer, 2009) but also with emerging viewpoints in human-agent interaction that emphasise re-envisioning robot design through a relational lens when addressing operational challenges (Lupetti et al., 2019).

6.4.4 Summary

In summary, as agents become increasingly prevalent in urban environments, their operational challenges underscore the importance of eliciting assistance from bystanders. However, the misaligned task objectives and various contextual factors present a gap in effective strategies to facilitate such casual collaborations. Responding to Cila's call (Cila, 2022) for envisioning effective ways to foster human assistance, our research spotlights urban scenarios where robots get stuck as an example, exploring effective non-verbal strategies for them to seek help during operational difficulties.

6.5 Methodology

In recent years, design research has not only aimed to predict urban futures but also foster a collective vision and conversation on the harmonious coexistence of humans and agents (Crivellaro et al., 2015; Lupetti et al., 2019). Adding to this discourse our research aims to support this evolving narrative, emphasising the shift in human-agent collaborations from mere technological efficiency to the deeper interplay between humans and agents.

As intelligent technology gains increased agency (Cila et al., 2017), the conventional perspective of technology being a mere passive tool becomes incongruent (Sanches et al., 2022). Consequently, researchers are now advocating for involving technology as a 'participant' in the design process (Coulton and Lindley, 2019; Giaccardi and Redström, 2020). To subjectivise participants to the agent's perspective and integrate it into the design process, our design investigation employed role-play bodystorming activities. We contextualised casual human-agent collaboration in scenarios where occasionally immobilised urban robots require bystander assistance. Participants alternated between the roles of the robot and pedestrian in these scenarios, with each scenario presenting a task for the robot player to seek assistance from the pedestrian player.

Embodied design methods, such as bodystorming (Schleicher et al., 2010), offer a compelling intersection between our tangible sensations and cognitive processes, thereby fostering a heightened sense of bodily empathy in design processes (Abtahi et al., 2021; Gemeinboeck and Saunders, 2017; Pelikan et al., 2023). In the realm of human-agent interaction, various studies have ventured into the embodied design exploration centred on the notion of 'becoming' (Wilde et al., 2017; Gemeinboeck and Saunders, 2017; Gemeinboeck and Saunders, 2023; Gemeinboeck and Saunders, 2018; Dörrenbächer et al., 2020). These studies utilise physical prompts as tools to immerse designers directly into the agent perspective, thereby fostering a heightened sense of bodily empathy in the design process. Our methodology, inspired by these pioneering embodied design methods, uses physical probes to evoke a tangible sense of becoming a robot, enriching ideation based on bodily experience and empathy. The focus of embodied methods on in-situ comprehension and bodily empathy makes them particularly suitable for probing the intricate socio-technical facets of human-agent casual collaboration in public urban contexts.

6.5.1 Bodystorming scenarios

A notable challenge with embodied design methods in human-robot interaction research is their speculative nature, which can sometimes distance them from practical real-world scenarios. Acknowledging the importance of grounding these speculative methods in tangible realities, our methodology fuses speculative embodied methods with real-world scenarios. Our bodystorming activities are contextualised in real-world scenarios in which urban robots might encounter operational difficulties. These scenarios were drawn from a comprehensive online ethnography study we previously conducted. In this study, we analysed 117 user-generated videos that captured road users' casual encounters with delivery robots on TikTok [1]. From this analysis, we identified three typical scenarios in which an urban robot may face operational difficulties: (1) The robot is stuck and requires assistance to be pushed out. (2) The robot is unable to cross the road and needs someone to press the traffic light button for it. (3) The robot is blocked and requires people to clear a path for it.

Fig. 6.1.: Study setup overview: A detailed view of the robot costume (left) juxtaposed with the *Starship* delivery robot; Site setting (middle); Screenshot of session recording (right).

6.5.2 Scenario set-ups and robot costume

We utilised simple markers and physical props to replicate these scenarios. For example, we used masking tape to delineate the divisions between driveways and sidewalks, as well as to indicate zebra crossings (see Fig. 9.2, middle).

Low-tech prostheses and props have been shown to facilitate perspective shifting and stimulate imagination in human-robot interaction bodystorming (Dörrenbächer et al., 2020). Guided by these insights, our robot costume design sought to emulate the appearance and constraints of a box-shaped delivery robot. We narrowed

[1]https://www.tiktok.com/

the communication and interaction modalities of the robot player to exploring the help-requesting interactions of robots in abstract forms, in a minimal anthropomorphic manner. In addition, the design sought to exclude the potential effects of interpersonal communication when two participants can see each other.

The robot costume was made out of an $80\,\text{cm} \times 60\,\text{cm} \times 60\,\text{cm}$ cardboard box (see Fig. 9.2, left). The bottom was removed and replaced with a dolly, allowing participants to sit inside the box and move freely. In addition, the four walls and top surface of the cardboard structure were supplanted with one-way, see-through reflective film. This modification endowed the robot player with the ability to observe the external environment, while concurrently shielding the interior from outside view, thereby inhibiting any possibility of eye contact with external observers. The robot player was also provided with an adjustable stick pointer that they could hold and reach out from the top of the box, to imitate the flagpole featured on commercial delivery robots.

6.5.3 Participants

We conducted 4 focus group sessions with 17 expert participants (8 males, 9 females; aged between 18-44): the first three sessions each included 4 participants, while the final session accommodated 5. These participants came from diverse academic or professional domains related to urban robots (Tomitsch and Hoggenmueller, 2021), including four PhD students in human-computer interaction and human-robot interaction, three PhD students in urbanism, two postdoctoral researchers in robotics, three interaction designers, and five postgraduate students specialising in interaction design. The selection of participants enhances the discourse by integrating their specialised expertise, while simultaneously bringing their lived experience as pedestrians into the role-play activity. Participants were recruited from our university's mailing lists, flyers, and social networking platforms, following the study protocol approved by our university's human research ethics committee.

6.5.4 Study procedure

Warm-up activity

Prior to the formal bodystorming sessions, we asked participants to put on the robot costume to experience role-play, following simple instructions such as *'I am tired of working, I am gonna quit!'*. The goals for this warm-up activity were to (a) foster a

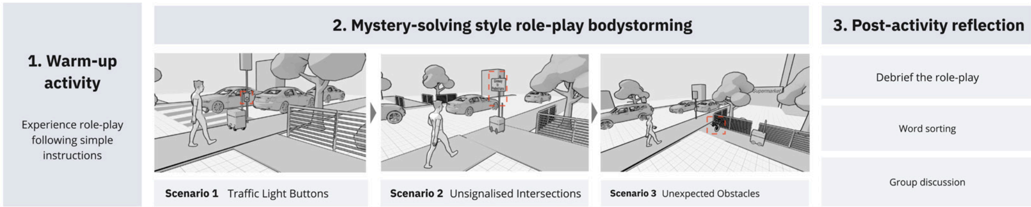

Fig. 6.2.: The overview of study procedure

playful mindset, (b) let participants get familiar with each other, and (c) physically and mentally prepare everyone to engage in the following bodystorming ideation.

Mystery-solving style role-play bodystorming

We adopted a mystery-solving style role-play bodystorming inspired by a similar approach used by Abtahi et al. (2021). In their design activity, participants acting as robots presented designers with obscured issues (e.g., an occluded camera) challenging them to identify and resolve these problems. This approach suited the unpredictability of casual collaboration in our context.

In each bodystorming session, two participants spontaneously volunteered to play the main roles of either the robot or the pedestrian. The remaining participants could either observe or actively engage by portraying ancillary elements within the traffic scenario, such as vehicles (see Fig. 9.2, right). All participants were unaware of the study objectives, ensuring unbiased participation from both robot and bystander players. The robot player and pedestrian player were provided with a printed storyboard that introduced the scenario, along with text instructions that outlined their tasks (see an example text instruction in Table 6.1). For those playing the pedestrian role, the instructions provided merely the contextual background of their destination, prompting them to behave naturally. The instructions for the robot players contained information about the operational difficulties they would encounter, along with a secretive task of seeking assistance from the pedestrians and expressing gratitude if help was offered.

Prior to each bodystorming session, we first introduced the simulated terrain and walked all participants through the setup (i.e., the location of pedestrian sidewalks and driveways, other traffic infrastructure, etc.). After participants read and understood the storyboard and instructions, we asked the robot players to leverage any communication modalities other than human language to accomplish their secretive tasks. Once the activity started, the facilitators did not participate or intervene in

Tab. 6.1.: Sample text instructions for the traffic light button scenario. The tasks assigned to both participants are highlighted in *italic*.

Participant role	Text instructions
Pedestrian player	You are a pedestrian heading towards the nearby supermarket to buy groceries. You come across a delivery robot on your way there. *Please act and respond naturally to the situation, you are free to make any reactions you would like towards the robot.*
Robot player	You are a delivery robot carrying out a delivery task on an urban street and your destination is on the opposite side of the road. To get there, you have to navigate through an intersection and cross the road safely. *Upon arriving at the intersection, you notice that the traffic light is red, and you realise that you are unable to press the traffic light button. Your task is to request the pedestrian who is traversing the area to assist in pressing the traffic light button for you. You should also express gratitude to those who help you. (Remember you cannot speak human language.)*

any way. The activity ended either when the robot player successfully received help from a pedestrian player or when the pedestrian player left the robot player and reached their destination without providing assistance. All participants alternated between the roles of robot and bystander, repeating this process across three different scenarios.

Post-activity reflection

After each round of the bodystorming, participants who engaged in the activity reflected on their experience. The reflection for the robot player included how they asked for help and the rationales behind their actions, while the pedestrian player reflected on how they understood and reacted to the robot, as well as why they reacted in that particular way. To facilitate this reflection process, we replayed videos recorded during the activities.

To determine the desired characteristics of a robot when it seeks assistance from bystanders, we conducted a word sorting activity following each round of bodystroming after participants debriefed their role-play. The word sorting activity is inspired by *Kansei Design* method (Nagamachi, 1995). The Japanese term *Kansei* refers to an individual's cognitive and affective responses to an experience, encompassing aspects such as aesthetics, emotions, feelings, impressions, and values. Kansei design aims to create products that resonate with customers' psychological feelings and needs, translating these intangible aspects into actionable parameters that can be utilised throughout the product design process. Its proficiency in discerning non-functional requirements from human preferences and needs suits our investigation of casual collaboration. .

We drew from the Kansei semantic dictionary proposed in (Kobayashi and Ota, 2000), which offers a comprehensive system of Kansei words that capture human impressions and feelings across three aspects: physical, social, and psychological. Our selection of terms was guided by this dictionary, related robotic research that employs Kansei design methods (Pakrasi et al., 2018), the Laban movement analysis which emphasises movement quality (Groff, 1995), and findings from our prior online ethnography study. The digital transcription of the word sorting board can be seen in Fig. 6.5.

The word sorting activity was facilitated on A2 size printed boards, with participants indicating their chosen words using stickers of various colors. During the word sorting, robot players chose words to describe their subjective feelings as robots in the bodystorming, using blue stickers, while participants other than the robot player selected words that reflected their perceived impressions of the robot, using yellow stickers. Throughout this process, participants also verbally elaborated on their feelings. Subsequent to this, all participants were prompted to set aside their assigned roles. They engaged in another round of word sorting, drawing from their own areas of expertise to pinpoint the desired attributes of a robot's help-seeking interactions using orange notes. This word sorting was further enriched by interviews and discussions where we encouraged participants to expound on their opinions.

6.5.5 Data collection and analysis

The focus groups were audio and video recorded, and observation notes were taken both during the sessions and afterward when analysing the session videos. We transcribed the interviews and made detailed observation notes based on video recordings captured during the bodystorming activity. We conducted a thematic analysis (Braun and Clarke, 2006) on both the interview data and the observation notes. This cross-analysis approach enabled us to gain deeper insights into specific observations and enriched the contextual data that supported the comments made during the interviews.

The first author examined the data from the first focus group session, thus generating preliminary codes and themes. This was followed by a one-hour coding meeting amongst the three authors to deliberate upon this initial coding scheme. The coding scheme was refined based on the collective feedback and applied by the first author to code the data derived from the second and third sessions. During this process, flexibility was maintained for the generation of new codes, allowing for their integration into either a new theme or an existing coding scheme. Subsequently, another coding meeting was convened amongst the authors for further iteration of the coding scheme. Upon reaching a collective agreement, the first author coded the data from the fourth session and refined the coding from the previously analysed three sessions. This iterative and collaborative process ensured a holistic analysis of the data, leading to more concrete conclusions drawn from the focus groups.

6.6 Findings

This section begins with the observed non-verbal communication strategies employed by robot players to initiate assistance, supplemented with insights into the reactions of pedestrian players in scenarios replicating encounters with urban robots. Following that, we shift our focus to the bystander perspective by reporting on the diverse factors that influence their decision to offer assistance or not. Subsequently, we synthesise these perspectives in reporting word sorting results, revealing the desired characteristics of robot help-seeking behaviour. It is worth noting that the findings discussed in this section may not exhaustively encompass the spatio-temporal and political complexities of urban settings, which are difficult to fully replicate in bodystorming design activities.

Fig. 6.3.: Screenshots from the bodystorming session capturing interactions between robot and pedestrian players: Robot player P9 tilts his box costume towards P11, making contact (left); Pedestrian player P1 gestures towards the button, seeking robot player P4's confirmation (middle); Pedestrian player P17 waves in response to robot player P15's spinning motion (right).

6.6.1 Strategies of robot players to elicit help

Addressing bystanders One of the challenges for robot players was to capture the pedestrian's player attention and initiate interaction with them. During the bodystorming activity, robot players employed various strategies to address bystanders in order to gain further assistance. Robot players frequently utilised rapid movements of the pole, thereby generating noticeable noise. This approach served to attract attention before initiating subsequent communication with pedestrians (n=7). This approach was corroborated by five participants who identified the robots' noise and shaking poles as the primary factors that compelled them to stop and further observe.

When not receiving further assistance, some robot players directly addressed the nearby pedestrians using various methods (n=5). They oriented themselves toward the pedestrian players to face them directly, or slightly moved towards them, which served as an indication to those individuals that they were being called out for assistance. As P15 illustrated when referring to the moment the robot player turned its front towards him and approached: *'It started walking directly towards me, and that's when I realised it needed assistance from me.'*

After some pedestrians remained indifferent to the robots' request, a few robot players took their actions a step further. They proactively chased departing pedestrians, obstructed their path, or even engaged in physical contact with them. For instance, robot player P9 tilted his box costume towards the pedestrian player P11 and rubbed against him (as shown in Fig. 6.3, left). These pursuing behaviours generally elicited a sense of discomfort among participants, causing them to maintain a considerable distance from the robot player (P3, P9), or even escape from the situation entirely (P7, P11). During the subsequent interview, P11 described the interaction as *'needy'* and *'creepy,'* prompting a strong desire to flee.

Cueing intentions Upon capturing the attention of pedestrian players, robot players used their body's orientation or pointer's directionality to further convey their intentions. They either oriented themselves accordingly or used the pointer to indicate their intended directions or objects they needed assistance with. Such non-verbal cues, while informative, may not always ensure clear communication. This was underscored during bodystorming when three pedestrian participants sought additional confirmation from the robot player. For example, when robot player P4 oriented himself towards and paused upon the traffic light button, P1 approached, pointed at the button and looked at P4, asking, *'Is it?'* (see Fig. 6.3, middle).

To enhance clarity, the robot player responded by adding motions in the desired direction or repeating the same pointing gesture. Robot player P4 responded to P1 by stepping back and moving forward towards the traffic light button again as confirmation. Recognising this, P1 then assisted by pressing the button. In this manner, both parties intriguingly communicated through a blend of verbal and non-verbal exchanges.

Displaying emotions Even though participants were not given any external communication modalities apart from the robot body – consisting of a box and a pole – six of the participants attempted to convey emotions through movements or sound. A common emotion exhibited by participants (n=5) was anxiety when pedestrians did not offer help during the role-play. This anxiety was manifested through frequent and intense shaking of the pole or twisting of the robot's body. The displayed emotion raised empathy among participants. P17, for instance, reflected on an instance where the robot player was impeded by an obstacle and energetically waved its pole towards her: *'[. . .] it (the robot) seemed very anxious. Then I quickly realised that it was this thing that was blocking it.'* As a result, three out of the five participants who initially didn't assist the robot began to pay heightened attention and acknowledged the situation. This ultimately prompted them to step in and provide assistance.

Four robot players tried to express gratitude after receiving help by expressing joyful emotions through their movements, such as hopping up and down (P6) or spinning around (P15), as well as through sound, like vocalising an uplifting tune (P7, P1). Displaying these joyful emotions prompted responses such as nodding (P9) and waving (P17, as shown in Fig. 6.3, right) by pedestrian players. P17 drew a connection between waving to the robot and her experience of encountering small animals, explaining, *'Because I tend to greet small animals, or things that I find cute or have emotions.'* Furthermore, P7 conveyed a sense of satisfaction when seeing the robot spinning around, stating, *'I felt very satisfied because I believe it has feelings. [. . .] I help it and it is happy, which also makes me happy.'* P9, commenting on the joyful tune produced by the robot player P11 following his assistance, noted, *'It made me feel like, alright, I did the right thing.'*

Demonstrating repetitive patterns Having discussed the three primary components of communications — addressing bystanders, cueing intentions, and displaying emotions — another notable observation emerged. Robot players frequently assembled these components into discernible repetitive patterns, resembling the predictable and programmed behaviours generally associated with robots (n=7).

P7, for instance, developed a unique routine to signify a pathway obstructed by an obstacle: she advanced towards obstacles while emitting two flat-tone beeps,

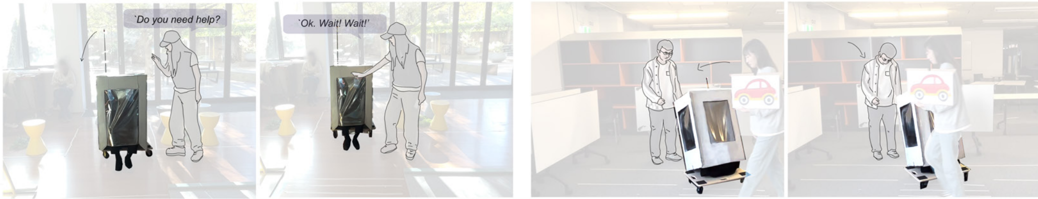

Fig. 6.4.: Communication between robot and pedestrian players: P8 inquires about robot player P6's needs, while P6 responds by pointing with the pole (left); Robot player P14 adopts a 'bow' gesture towards the pedestrian player, eliciting a corresponding bow in return (right).

moved back with an up-tone beep, and paused briefly before repeating this cycle multiple times. Her rhythmic auditory cues were synchronised with her physical movements. She later explained that this use of repetitive movements and audio cues was reflective of her *'imagination of the robot having some program behind the system.'* Similarly, P2 adopted a pattern that combined cueing intention and addressing bystanders by repeatedly turning towards the pedestrian player, returning to the original position, and then turning towards the obstacles blocking its path.

Eight participants indicated that the recognition of programmed machine-like behaviour augmented their understanding of a robot's intent to communicate. In contrast, movements lacking a recognisable pattern were sometimes perceived as *'erratic'* or *'malfunctioning'*. The repetitive movement patterns reminded four participants of situations where domestic cleaning robots get stuck and repeatedly attempt to move back and forth. The familiar motion patterns helped participants form associations and understand the robot's need for help.

In addition to enhancing understanding, recognising repetitive patterns in the robot's behaviour also potentially improved participants' confidence in the robot's abilities. The robot's consistent adherence to certain rules communicated a sense of control over its actions, as P9 noted, *'I think the robot knew what it wanted.'* P7 indicated that the repetitive patterns in the robot's movements signify predictability, allowing *'the pedestrian (to) anticipate what's gonna happen.'*

6.6.2 Factors shaping bystander decision to offer or decline assistance

Preconceptions of agent autonomy Our study underscores the prevailing perception among participants that service robots should operate with complete self-sufficiency and efficiency (n=10). This forms a major reason for participants' reluctance to assist robots. For instance, P9 shared his presumption about robots' capabilities to manage all tasks autonomously, stating, *'I thought the robot was able to do everything itself.'* Such misconceptions can foster misunderstandings about the actual capabilities and needs of these robots, an aspect further highlighted when P9 continued, *'[. . .] so I didn't realise the robot was asking me to help.'* This expectation subsequently instigated skepticism among six participants regarding the functional utility of service robots that require human intervention. This sentiment was articulated through comments like,*'If you have to work for them, then what's the point to have a robot'* (P6). P7 further noted a decline in trust due to the robot's need for help, contrasting it with her expectation of a service robot's role as a functioning entity, stating *'As a working robot (i.e., service robot), they kind of made me feel like untrust(worthy). [. . .] so they (have to) work perfectly.'*

Interestingly, when debriefed about the actual scenario, there was a notable shift in the attitudes of four participants. They came to understand that the robots' challenges arose from external factors outside their capabilities (e.g., obstacles purposely placed by humans) rather than any inherent malfunctions. P4 underscored this realisation, remarking, *'then it's the human's fault (for placing the obstacle)'*. The reassignment of responsibility for the robot's immobilisation not only improved participants' inclination to assist but also enhanced their empathy towards the robot's predicament. P9 summarised this change of mind, noting that in this case the robot is *'in need of help rather than being needy'*.

Absence of responsibility The notion of being a mere bystander or pedestrian, devoid of any responsibility towards the enacted robots, emerged as a primary factor influencing the decision not to assist among ten participants. This sense of detachment made them reluctant to invest their time and effort in helping 'something' they didn't feel accountable for. P14 particularly highlighted resistance to being perceived as *'free labour'* for commercial enterprises, posing the question: *'why should I spend my time helping something that is making a profit?'* However, they later nuanced this statement by adding: *'If it (the robot) is for a non-profit purpose, then I might be inclined to help, even if it means me being a bit delayed.'*

The concerns of getting entangled in potential troubles further discouraged five participants from offering help. P1 expressed this concern, stating *'I am afraid of touching it and breaking things. [. . .] It could cause trouble if we touch it.'*

Unfamiliarity with robotic technology Seven participants expressed hesitation to assist the robot due to a perceived lack of expertise. They felt ill-equipped as *'random pedestrians'* (P7) to provide assistance to the robot, a task they believed was best left to professionals, as indicated by two participants.

The unfamiliarity with robotic technology sparked safety concerns among six participants, hindering them from offering help. This was further corroborated by our observations of five participants who actively distanced themselves or avoided the robot when it approached them for assistance. This evasion stemmed from the uncertainty about potential risks linked to the robot's predicament, as P7 stated, *'I don't know if it's a tiny little issue or if it's going to explode or something.'*

Intrinsic motivation: empathy and emotional responses Our interviews indicate that intrinsic motivation plays a compelling role in promoting bystanders to assist the robot, with feeling empathy being the primary motivator (n=8). Participants described the robot using terms like *'depressing'*, *'frustrated'*, and *'helpless',* signifying their ability to infer the robot's emotional states through observation of its movements within given contexts. For example, P9 noted that observing the robot's body swaying in an appeal for help prompted an association with vulnerable individuals, stating *'[. . .], so (it's) like a child needs help or an old person needs help'*.

In addition to empathy, six participants reported experiencing a sense of emotional reward, capturing feelings of *'fulfilment'*, *'satisfaction'*, and *'delight'*, following their actions to assist the robots. P2, for example, articulated this sentiment as, *'You helped it and witnessed it moving forward, which brings you a sense of satisfaction.'* Moreover, the gratitude exhibited by the robot reportedly amplified these emotional rewards (n=4).

However, it was also evident that some participants demonstrated a reduced level of empathy towards robots. Specifically, P1 drew comparisons with other entities, affirming readiness to *'stop for a dog or a cat, but not for a robot.'* He justified this attitude with his belief that *'you can't expect to treat a robot as a human or as a living animal.'* In one session, P15, who assumed the role of a vehicle driver, further underscored this perspective by simulating a horn by knocking on the board prop and voicing their impatience by yelling at the robot. Their behaviour was justified by their assertion that the robot *'cannot be viewed as human.'*

Extrinsic motivation: entertaining value and material reward Apart from intrinsic motivation, our interviews highlighted the role of extrinsic motivation, stemming from both tangible and intangible incentives, in fostering helping behaviours towards robots.

Six participants anticipated entertainment value from helping robots, viewing this form of intangible incentive as an additional incentive to offer assistance. As articulated by P9, the incorporation of a *'surprise element'* into the interaction could further *'spark joy.'* P12 also mentioned the potential of *'transforming it (assisting robots) into a more game-like experience'*.

Furthermore, two participants felt that their prosocial actions should also yield tangible advantages for them. They suggested the introduction of material rewards, such as vouchers or discounts from the company that implements the robot, could further stimulate their willingness to assist. This perspective was rooted in their belief that as bystanders, their prosocial behaviour towards the robot was not directly *'benefiting'* them.

6.6.3 Desired robot characteristics

Based on the results of the word sorting activity and insights derived from the participants' discussions, we identified three characteristics that help-seeking robots could implement, which we present in this section.

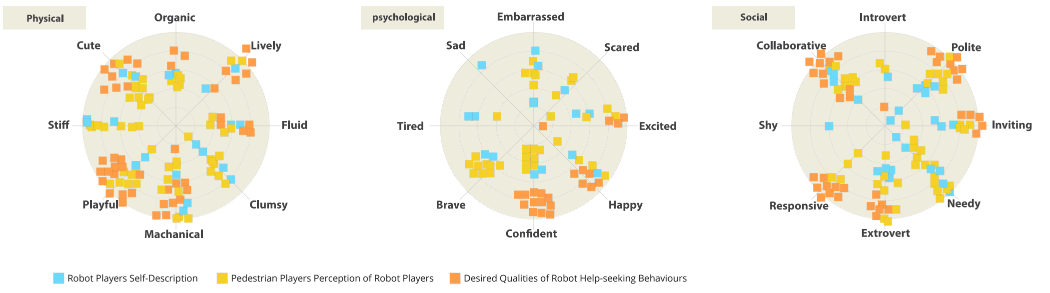

Fig. 6.5.: Digital transcription of the word sorting results

Vibrantly mechanical The physical sensations experienced by robot players are evenly distributed among all words with a slightly higher number of *'clumsy'* (n=4). This choice primarily stems from the physical limitations of moving within the robot costume.

There's a noticeable overlap between the perceived physical qualities of the robot player and the desired attributes. In particular, *'mechanical'* was selected as perceived quality (n=9) and desired quality (n=10). Similarly, the same pattern was observed in *'playful'* (8 for perceived quality, 14 for desired quality), and *'cute'* (11 for perceived quality, 8 for desired quality). This correlation implies that the robot players' behavioural strategies, to some extent, met participants' expectations for how a robot should act when seeking assistance, especially concerning these attributes. The movement of the robot players, encapsulated in the minimalist abstract box-shaped costume, inherently conveys an impression of cuteness without the need for additional embellishments. As P12 expressed, *'I feel its existence is cute enough already. Just imagine you're on the road, helping a little robot, and it goes "dibbly-dobbly" as it moves forward. It's already incredibly cute, and there's no need to add additional design language.'* While some participants also selected *'lively'* and *'organic'*, they view these as elements that can be added to the overall mechanical nature of the robot to enhance the expressiveness. P13 emphasised the importance of using these elements thoughtfully to *'avoid creating the uncanny valley effect.'*

Cheerfully confident In regards to the psychological feelings of robot players, there was no clear tendency being identified in the word sorting, which may imply that this was highly subjective. When it comes to other participants' perceptions of the robot player, *'brave'* (n=9) and *'confident'* (n=8) emerge as two dominant qualities. Participants highly commend the robot player's efforts to find solutions in challenging situations. P16 pointed out the robot's vulnerability and the hazards and difficulties of its environment. She articulated, *'(the robot) dared to cross the road on his own and was thinking about how to do it.'* when it was *'dangerous because there were no traffic lights for (it)'*. P2 contemplated the perceived braveness, projecting the psychological state that humans have when seeking help from strangers onto the robot. She expressed that the robot *'needs help (and asks for it), as it needs to use courage to convey the help it needs.'*

In terms of the desired psychological attributes, participants generally favoured positive emotions. The term *'confidence'* (n=12) emerged as the predominant expectation that people had for the robot's demeanour. P7 expressed this perspective by describing a service robot as *'some kind of professional stuff'*, implying the need for the robot to exhibit characteristics that align with expected proficiency. In addition, participants generally expected the robot to display *'happy'* (n=6) emotions after receiving help.

Descriptors of negative emotional valence (e.g., *'sad'*) were not considered as desired qualities for help-seeking robots. P2 offered an enlightening comment that a casually-encountered robot exhibiting sadness while seeking assistance was reminiscent of street beggars, leading to feelings of what they described as *'emotional blackmail.'*

Responsively outgoing The self-assessed feeling of *'needy'* emerged as the most frequently chosen term among robot players (n=7), indicating that they experienced a sense of helplessness and a perceived necessity for human aid as a robot in the given situation. To elicit help, most of the robot players opted to project a more approachable character, frequently choosing descriptors like *'extrovert'* (n=4), *'collaborative'* (n=4) and *'inviting'* (n=3). In contrast, only two robot participants resonated with terms like *'shy'* and *'introvert'*.

Other participants' perceived robot social quality aligned with the self-assessed social attribute of robot players, with *'needy'* (n=15) and *'extroverted'* (n=8) being the most frequently chosen terms. In terms of the desired social qualities, although *'extroverted'* was still among the preferred terms, participants placed a greater emphasis on communication qualities such as being *'polite'*, *'responsive'* and *'collaborative'*. P2 highlighted the importance of politeness, even when the robot is in urgent need of help, saying, *'At the same time, when you try to attract everyone's attention as much as possible, you also need to be gentle towards others.'* The desired *'responsive'* quality reflects participants' expectation of receiving feedback after offering help. For example, P17 expressed feeling disappointed if she helped the robot without receiving any response from it.

6.7 Discussion

Drawing from the findings of the previous section, we identify three design considerations (C1-3) for fostering casual human-agent collaboration. In addition, we reflect on the strengths and limitations of the bodystorming design activity employed in our study.

6.7.1 Expressiveness through functionality-oriented form

Given humans' innate psychological tendency to interpret social cues from moving objects (Heider and Simmel, 1944), physical movement has become a pivotal medium in human-agent interaction to facilitate social communication (Zuckerman and Hoffman, 2015; Zaga et al., 2017; Gemeinboeck and Saunders, 2017; Luria et al., 2017; Anderson-Bashan et al., 2018). An example of extreme abstraction with minimal movement serving as social cues is the *'Greeting Machine'* (Anderson-Bashan et al., 2018) – a small ball rolling on a bigger dome in varied trajectories. This design effectively elicits both positive and negative social encounter responses. Similar to *'Greeting Machine'*, participants in our design investigation were constrained by a robotic costume made of a box and a pole that had only minimum expressive capabilities. This costume had no extensions beyond the basic form factor of a conventional delivery robot that is primarily intended for the task of transporting goods. Nonetheless, subtle cues, such as the robot's orientation in its shape (i.e. orienting the front of the box costume toward an object) or the directionality of simple components (i.e., pointing in the intended direction using the pole), proved effective in addressing bystanders and conveying the robot's need for assistance.

This was evident, as in all the sessions, pedestrian players accurately understood the robot player's request for assistance. In addition, we even witnessed conversations formulated through the back-and-forth interplay between pedestrian inquiries and the subtle motions of robot players (as shown in Fig. 6.4, left)

In addition to empathising with the robot's feelings of frustration and vulnerability when seeking help, it was evident that people also recognise social signals gestured through subtle movements, such as gratitude. For instance, a simple tilt of the box-shaped robot body, can be perceived as a 'bow', even prompting the pedestrian player P15 to bow back (as shown in Fig. 6.4, right).

As pointed out in our literature review, linguistic utterances have been central in human-agent collaboration (Seaborn et al., 2021) and represent a key method for help-seeking requests (Backhaus et al., 2018; Srinivasan and Takayama, 2016; Hüttenrauch and Eklundh, 2006) given their effectiveness in conveying information. Nonetheless, challenges such as cultural and language barriers, cognitive load, and issues related to noise and distortion in public settings limit their utility in the context of casual human-agent collaboration in public spaces. In addition to that, our study revealed further concerns regarding the appropriateness of agents verbally asking for help in urban public contexts (n=7). P1, for instance, suggested it could be a *'bit abrupt or out of place'* if a robot suddenly started to talk human language on the street, underscoring the need for robots to have their own unique, natural communication modes. Additionally, safety concerns were expressed by three participants who suggested that language used by robots might potentially distract other road users. Notably, P14 expressed potential discomfort in feeling exploited by commercial entities when robots use human language to solicit assistance, suggesting a *'feeling of being used as free labour for those commercial companies'*.

C1 - The design of agent help-seeking strategies should leverage the inherent expressiveness found in the functional aspects or form of the agent. While ensuring effective initiation of help-seeking requests, these implicit communication channels can prevent from being viewed as disruptive.

6.7.2 Adherence to perceived agent social categories

Robots and intelligent agents, growing rapidly in sophistication and sociability, have spurred enhanced research into agent social identity (Hogg, 2016), delving into aspects like gender (Eyssel and Hegel, 2012), age (Edwards et al., 2019), and race (Bartneck et al., 2018). This trajectory was echoed at a recent workshop (Winkle et al., 2021), which emphasised the importance of designing robots that can effectively convey social identities to optimise human-robot interaction outcomes. While this workshop primarily centred on social identities associated with specific attributes (i.e. gender), our findings broaden this scope to encompass wider social categories (e.g. occupations), which should be considered in the design of casual collaborations between agents and bystanders.

In our investigation of the help-seeking delivery robot, participants perceived these robots primarily as service providers or professional workers. This perception led them to expect high proficiency from these robots, favouring the robot presenting qualities reminiscent of confidence over neediness. Consequently, even when assistance was necessary, participants displayed a general reluctance to interact with robots that seemed overly needy or showcased negative emotions. This inclination stands in contrast with studies on eliciting human prosocial behaviour towards social companion robots (Connolly et al., 2020; Daly et al., 2020) (e.g., robotic pets). In these settings, negative emotional expressions in robots often serve as a catalyst, motivating individuals to step in and offer help. This difference could be rooted in the distinct perceived categories: '*worker*' versus '*companion*'. In public urban settings, intelligent agents participate integrally in various facets of urban life. As a result, they embody a wide range of social categories, from service providers (e.g., delivery robots (Gehrke et al., 2023), street cleaning robots (Jeon et al., 2017)) and authoritative entities (e.g., smart traffic regulators (Lee et al., 2022), patrol robots (Szocik and Abylkasymova, 2022)) to street entertainers (e.g., playful urban robots (Hoggenmueller et al., 2020b; Lee and Jung, 2020)).

C2 - To respond to real-world expectations and social norms, the design of agent help-seeking strategies should adhere to and match with their perceived social categories (e.g., occupation).

6.7.3 Curating incentives: material rewards, act of care, or playful engagement

Though in 7 out of 9 sessions, pedestrian participants offered help, 4 of them mentioned they might not behave the same way in real-life settings. Furthermore, the misaligned objectives and the imbalanced benefits between agents and bystanders in such casual collaborations highlight the need for incentives.

Previous research on bystander assistance for commercially-deployed robots has divided 'help' into two broader categories: either 'helping-as-work', emphasising precarity and invisible labour, or 'helping-as-care', which accentuates the emotional and relational dynamics of help (Dobrosovestnova and Reinboth, 2023). This work sheds light on the inherent ambiguity of these helping behaviours and prompts a rethinking of robot design to better shape these engagements. Our focus group findings resonate with this notion, while also shedding light on how different perspectives on helping robots call for various forms of incentives.

Offering material rewards, such as vouchers or discounts from companies deploying robots, turns casual collaborations into mutually beneficial exchanges. This model of paid crowdsourcing, evident in cases like identifying shared bicycle locations (Griffin and Jiao, 2019) or urban data collection on platforms like OpenStreetMap (Crooks et al., 2015), could be adapted for interactions with intelligent agents in public spaces. By framing casual collaborations as beneficial exchanges through material rewards, it can effectively align disparate objectives between parties into actions that are mutually advantageous.

In our study, empathy – as an act of care – emerged as a predominant motivator for offering assistance, manifested as a form of internal incentive. Empathy, essential in shaping communication and social bonds, has been underscored as a central component in human-agent interactions Bickmore and Picard, 2005. A robust body of research validates robots' capacity to elicit empathetic responses from humans (Kwak et al., 2013; Riek et al., 2009; Rudovic et al., 2018). Correspondingly, studies on social robots have shown that these forms of empathy can drive prosocial behaviour, compelling humans to intervene against robot mistreatment (Connolly et al., 2020) or engage in affectionate actions, like petting (Heerink et al., 2012). Our findings resonate with these prior studies, suggesting that individuals exhibit empathy also towards public agents in need, driven by the observation of context and agent expressions.

In addition to viewing helping robots as a form of work or act of care, 'helping-as-play' has emerged as another perspective in our findings, for which the resulting entertaining value can function as an incentive. Playful strategies have been used in various human-agent interaction settings, such as motivating children's learning (Ahtinen and Kaipainen, 2020) or encouraging factory workers in collaboration with robots (Chowdhury et al., 2021). Furthermore, it has been shown to effectively engage the public and generate enjoyable experiences among bystanders (Lee and Jung, 2020; Hoggenmueller et al., 2020b). One of the primary challenges for urban robots to ask for help from bystanders is convincing them to invest their time and tolerate potential disruptions. The inherent playfulness in humans could potentially act as an incentive for casual collaborations by transforming disruptions into pleasure and enjoyment. That being said, 'helping-as-play' also needs to be carefully employed, as it can present ethical concerns similar to those in 'helping-as-care' (Dobrosovestnova and Reinboth, 2023).

C3 - To compensate for the misaligned task objectives in casual human-agent collaboration, the design of agent help-seeking strategies should incorporate appropriate incentives, transforming assistive behaviours into experiences that benefit both parties.

6.7.4 Reflections and limitations of bodystorming design activity

The physical constraints introduced by the robot costume, such as limited field of view, changes in perspective, and restricted mobility, while not capable of entirely replicating a robot's perspective, facilitated participants in departing from a conventional human viewpoint and immersing themselves in the sensations of robotic alienation and otherness (Dörrenbächer et al., 2020). As articulated by P5, *'There's a sense of feeling out of place or not quite fitting in. It seems like there are no peers of my kind in the surroundings. Everyone else is tall, and I am short, so I feel a bit out of place or different.'* This sense of otherness could contribute to participants' emotional engagement when they assumed the robot role, which was evident in the frequently conveying sentiments of *'frustration'* or *'depression'*. Additionally, beyond mere empathy with the robot's emotional state, the robot players also displayed a recognition of its societal function (i.e. its duty as a delivery service entity). For instance, P4 suggested feelings of *'motivated'* and *'happy'* when he *'could continue working'*. This profound resonance with the agent's perspective underscores that our bodystorming approach effectively incorporated the agent's perspective into the design exploration. However, it is worth noting that, despite the effectiveness of the physical probes in consciously shifting participant's sensations towards the perspective of an agent (Dörrenbächer et al., 2020), it is impossible to completely transcend the human standpoint through these methods as our human nature inherently separates us from things (Spiel and Nacke, 2020).

Consequently, the 'participation' of agents in the design process surfaces tensions between humans and agents that stem from the misalignment in goals and benefits in a casual collaboration encounter. P9's behaviours while playing the robot role offer a striking example. He assertively used the robot costume to brush up against the pedestrian player's chest — a distinctly pushy gesture meant to force attention and assistance. He later admitted, *'I was about to give up being nice'*, and even pondered, *'That's why I was considering adopting a more aggressive strategy. I thought, I might just try pushing him onto the road.'*. This elicitation of tension and physical friction is less likely to surface in methods that take a purely human-centred perspective or those that rely solely on cognitive abilities. Furthermore, this tension was leveraged to stimulate design ideation, exemplified by P9's subsequent ideas that emerged from this physical friction. He suggested infusing robots with seemingly annoying nudging behaviours and *'creating entertainment value'* to possibly uplift people's moods and thus promote pro-social behaviour.

Despite the strengths of our approach in generating design insights, we acknowledge its limitations. Discussions and reactions concerning helping a casually encountered agent were elicited by role-playing activities, without the incorporation of real technology. Even though the immersive nature of the replicated scenario and participant engagement is evident, the absence of real intelligent agents and the artificial nature of scenarios replicated in laboratory settings might limit the direct applicability of our findings. Acknowledging these inherent limitations of bodystorming method, future research should validate and refine our design considerations through more spontaneous interactions between humans and high-fidelity artifacts (e.g., through Wizard of Oz testing (Dahlbäck et al., 1993) or virtual reality study (Villani et al., 2018)).

6.8 Conclusion

Intelligent agents are increasingly transitioning into uncontrolled settings that often may challenge their operational capabilities. While collaboration between humans and agents can offer means to overcome these challenges, to date little is known about how to create effective and engaging human-agent collaboration in casual settings (e.g., involving surrounding bystanders).

Through employing bodystorming and real-world help-seeking scenarios encountered by urban robots, we uncovered potential help-seeking strategies through participants' enactments as robots, including addressing bystanders to initiate interaction and using non-verbal cues to communicate intention and request. Furthermore, the display of emotions and demonstrating repetitive patterns has been found to ease help-seeking requests. Taking into consideration the reactions of pedestrian players from our bodystorming activities, we further offered insights into the factors influencing people's response to robot's help-seeking requests and identified desired robot characteristics.

Synthesising insights from both robot and bystander perspectives, we conclude with a set of design considerations for help-seeking agents that operate in uncontrolled environments. These considerations include promoting expressiveness, ensuring alignment with agent social categories, and curating appropriate incentives. Findings from our design exploration and considerations for implementing help-seeking strategies provide a foundation for creating intelligent agents that operate in uncontrolled environments and aim to facilitate casual collaboration that is mutually beneficial to humans and agents.

7 Encouraging Bystander Assistance for Urban Robots: Introducing Playful Robot Help-Seeking as a Strategy

7.1 Preamble

Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch. Encouraging Bystander Assistance for Urban Robots: Introducing Playful Robot Help-Seeking as a Strategy. In *Proceedings of Designing Interactive Systems Conference (DIS '24)*

Building on the design investigation in Chapter 6, this chapter embeds the design considerations into a playful help-seeking strategy to encourage bystander assistance for urban robots. A VR lab study was conducted to evaluate this strategy, comparing it with existing verbal and emotional help-seeking approaches identified in related literature. The help-seeking scenarios investigated in the study were identified in Chapter 3. The aim of this chapter is to investigate the effectiveness of the playful help-seeking strategy. These insights contribute to design implications for supporting emergent collaboration between bystanders and urban robots. Thus, it continues to answer RQ2 *"How can we design interactions that facilitate casual collaboration between bystanders and urban robots?"* Furthermore, the study examines the impact of such casual collaboration on bystanders' experiences, moods, and attitudes toward the robot, thereby also addressing RQ3: *"How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?"*

This chapter was originally published as a paper at the ACM Conference on Designing Interactive Systems (DIS) and is available in the ACM proceedings of this conference. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

7.2 Abstract

Robots in urban environments will inevitably encounter situations beyond their capabilities (e.g., delivery robots unable to press traffic light buttons), necessitating bystander assistance. These spontaneous collaborations possess challenges distinct from traditional human-robot collaboration, requiring design investigation and tailored interaction strategies. This study investigates playful help-seeking as a strategy to encourage such bystander assistance. We compared our designed playful help-seeking concepts against two existing robot help-seeking strategies: verbal speech and emotional expression. To assess these strategies and their impact on bystanders' experience and attitudes towards urban robots, we conducted a virtual reality evaluation study with 24 participants. Playful help-seeking enhanced people's willingness to help robots, a tendency more pronounced in scenarios requiring greater physical effort. Verbal help-seeking was perceived less polite, raising stronger discomfort assessments. Emotional expression help-seeking elicited empathy while leading to lower cognitive trust. The triangulation of quantitative and qualitative results highlights considerations for robot help-seeking from bystanders.

7.3 Introduction

Robots are evolving beyond their traditional roles in semi-controlled environments, such as industrial and domestic settings, and are increasingly being deployed in more dynamic and unpredictable urban spaces. In these urban spaces primarily designed for human use, robots may encounter situations that extend beyond their pre-programmed abilities, necessitating human intervention for effective operation (Nanavati et al., 2021). This challenge is evident in recent field observations, which reveal instances where urban robots require human assistance for tasks like pressing traffic light buttons (Pelikan et al., 2024), navigating unpredictable obstacles (Weinberg et al., 2023; Pelikan et al., 2024) and temporarily altered streetscapes (Pelikan et al., 2024; Dobrosovestnova et al., 2022), or managing conflicts with other road users (Gehrke et al., 2023).

While the primary focus of robotics has long been on developing robots that can autonomously complete tasks without or with little human intervention, the challenges encountered by urban robots highlight that technology alone may not always suffice (Veloso, 2018). This has led to increased interest in robots designed to seek human assistance when necessary (Cila, 2022; Nanavati et al., 2021). Furthermore, exploratory projects (Weiss et al., 2010; Smith and Zeller, 2017; Kinzer, 2009) and emerging design research perspectives (Lupetti et al., 2019; Kuijer and Giaccardi, 2018; Marenko and Van Allen, 2016) increasingly frame human-robot interaction as a symbiotic relationship, focusing less on a robot's individual capabilities and more on the mutual dependency between humans and robots.

Efforts in human-robot collaboration research have been directed towards enabling intuitive and seamless interactions between humans and robots, with humans predominantly cast in the role of collaborative working partners (Ajoudani et al., 2018). In urban environments, however, the people urban robots typically encounter and would approach for assistance are often bystanders, or as defined in research, '*incidentally copresent persons*' (InCoPs) (Rosenthal-von der Pütten et al., 2020), people who do not have the deliberate intention of engaging in interactions with the robot. This shift in how humans relate to nearby robots calls for the re-examination of existing strategies and the development of new interaction approaches that cater to the spontaneous nature of casual human-robot collaborations in urban settings.

Previous research focusing on the implications of bystander assistance for commercially-deployed urban robots has identified two broad strategies: 'helping-as-work', which considers assistance as invisible labour, and 'helping-as-care', emphasising the emotional and relational aspects of providing help (Dobrosovestnova and Reinboth, 2023). Extending this discussion, our study introduces a novel dimension: 'helping-as-play', which focuses on encouraging bystander assistance through playful interactions.

Playful strategies and the use of game elements has been found to be effective in various human-robot interaction contexts, from motivating children's learning (Donnermann et al., 2021; Chen et al., 2023) to enhancing collaboration between factory workers and robots (Chowdhury et al., 2021; Venås et al., 2024). Furthermore, it has been shown to effectively engage the public and create enjoyable experiences among bystanders (Lee and Jung, 2020; Hoggenmueller et al., 2020b). A major challenge for urban robots in soliciting assistance from bystanders lies in persuading them to invest time and manage potential disruptions (Nanavati et al., 2021). Leveraging the inherent playfulness in humans has the potential to entice bystanders into assisting robots by offering a moment of joy within urban environments.

To investigate this opportunity, we developed a series of playful help-seeking design concepts that implement the 'helping-as-play' strategy. To test their effectiveness, we compared our playful concepts with concepts that implement the aforementioned strategies: verbal help-seeking, aligning with 'helping-as-work' as evidenced by its prevalent use in human-robot teamwork settings (Knepper et al., 2015; Srinivasan and Takayama, 2016; Budde et al., 2018), and emotional expression help-seeking, aligning with ‘helping-as-care’ for its effectiveness in eliciting human empathy (Backhaus et al., 2018; Zhou and Tian, 2020; Urakami, 2023; Daly et al., 2020). These strategies were prototyped and evaluated through a virtual reality (VR) experiment involving 24 participants. Our comparative analysis assesses the quality of these help-seeking strategies in terms of their unambiguity, politeness, appropriateness, and effectiveness. Additionally, it examines their impact on people’s experiences and moods, as well as their influence on people’s attitudes towards the robot. Through our design process and evaluation study, we aim to thoroughly investigate the effectiveness of various help-seeking strategies in eliciting bystander assistance. Additionally, we seek to investigate their broader implications, thus advancing our understanding of how such spontaneous collaborations should be facilitated.

This paper makes the following contributions: (1) It introduces playful engagement as a novel strategy for urban robots to seek help from bystanders, along with three exemplary design concepts implementing this strategy; (2) It provides insights into different robot help-seeking strategies and their potential influence on bystanders’ experience and attitudes towards robots. This understanding further leads to design considerations of how such robot help-seeking should be facilitated, as well as reflections on the design of game-inspired playful help-seeking strategy. Our study extends the application of playful engagement beyond merely creating enjoyable experiences, demonstrating its effectiveness in supporting the increasingly prevalent casual collaboration between urban robots and bystanders, thus promoting reciprocal co-existence.

7.4 Related Work

7.4.1 Service robots in public spaces

Robots, once predominantly deployed in controlled and semi-controlled configurations such as industrial settings (Sauppé and Mutlu, 2015) and domestic environments (Schneiders et al., 2021), are now expanding their presence into public urban spaces, thereby increasingly becoming integral components of our urban landscapes. These robots provide services in various aspects of society, including sectors such as transportation and logistics, infrastructure maintenance, cleaning, and surveillance (Salvini, 2018).

Despite technological advancements endowing robots with increasing autonomous capabilities, the inherent dynamism and complexity of urban environments pose significant challenges to their operation. This was vividly demonstrated in several viral videos on social media, showing, for example, delivery robots struggling in Estonia's heavy snowfall (Palmipuu, 2021). Further, recent field observation studies of urban service robots have also documented instances where their operations were hindered by unexpected obstacles (Weinberg et al., 2023), the inability to manipulate traffic infrastructure (i.e., traffic light button (Pelikan et al., 2024), human activities occurring on the streets (Pelikan et al., 2024; Babel et al., 2022b), and bullying behaviours (Bršćič et al., 2015; Salvini et al., 2010).

Beyond the evident operational difficulties, these instances intriguingly highlighted the spontaneous and supportive behaviours demonstrated by passersby, showcasing a compelling facet of casually formed human-robot interaction. In the observation study conducted by Dobrosovestnova et al. (2022), passersby were observed clearing snow in front of the robot or giving it a gentle push to return it to its path. In (Weinberg et al., 2023), pedestrians voluntarily assisted immobilised robots by removing obstacles. In some cases, people have even interrupted their own activities to assist the robot, as exemplified by a window cleaner pausing their work to allow delivery robots to pass through (Pelikan et al., 2024). These observations underscore the potential of leveraging bystander assistance to enhance the operation of urban robots, resonating with the emerging perspectives in HRI that emphasise relational collaboration over solely technological independence (Weiss et al., 2010; Kinzer, 2009; Lupetti et al., 2019).

7.4.2 Robot help-seeking

In human-robot collaboration settings, robot help-seeking has been explored as an intentionally designed strategy to recover from inevitable situations that exceed the robot's inherent capabilities. Tested in a human-robot team assembling context, Knepper et al. (2015) equipped the robot with verbal communication ability to generate help-seeking requests for tasks like handling unreachable objects. To advance the understanding of verbal help-seeking, research further evaluated factors like ambiguity (Budde et al., 2018) and politeness (Srinivasan and Takayama, 2016; Budde et al., 2018) in framing requests, and their impact on the effectiveness of help-seeking. In addition to explicit and spoken-language help-seeking requests, some studies have successfully tested the use of implicit and non-verbal cues, such as movement (Kwon et al., 2018), as well as light and sound (Cha and Matarić, 2016), to elicit assistance from human collaborators. Furthermore, employing emotional expressions to elicit empathy has been explored as another strategy for encouraging collaborative assistance (Backhaus et al., 2018; Zhou and Tian, 2020; Urakami, 2023; Daly et al., 2020) or inducing bystander prosocial interventions during robot abuse (Tan et al., 2018; Connolly et al., 2020). For example, research has shown that when robots exhibited sad emotional expressions, people were more inclined to assist them, leading to quicker success in a collaborative game (Zhou and Tian, 2020).

Unlike structured human-robot team settings with shared goals between both parties, help-seeking in public spaces poses unique challenges due to misaligned objectives between robot and bystanders. Furthermore, research has shown that diverse factors such as activities bystanders are currently engaged in (Hüttenrauch and Eklundh, 2006; Kerstin et al., 2014; Rosenthal et al., 2012), the robot's apparent legitimacy and perceived risk (Booth et al., 2017a), and the bystander's trust in and perceived competence of robots (Cameron et al., 2015), collectively influence their willingness to offer help. However, tailored design strategies or investigations that specifically focus on robot help-seeking from bystanders remain limited. Some studies have adopted verbal help-seeking (Rosenthal et al., 2012; Liang et al., 2023) which has been predominantly used in traditional human-robot collaboration settings, and a few have explored broader communication modalities, examining the interplay of movement with speech (Holm et al., 2022; Kerstin et al., 2014). Thus, the increasing need for assistive behaviours towards robots in public spaces calls for designers to imagine new interaction strategies to engage bystanders in casual collaboration with robots (Cila, 2022).

7.4.3 Playful and gameful design in human-robot interaction

Over the past two decades, technology has become ubiquitous, expanding beyond the context of the workplace. This has marked a significant paradigm shift in the field of interaction design (Harrison et al., 2007), challenging previous values such as efficiency and placing a stronger focus on meaning-making and enhancing the experiential qualities of interaction. This shift has also resulted in the rise of commercial social robots, as well as numerous examples from research, designed to promote playful engagement while striving for higher-level goals. Examples include playful robots that provide companionship to people in domestic contexts (Zuckerman et al., 2020; Ye et al., 2023; Sirkin et al., 2015a), support children's learning (Lupetti, 2020), promote creative and critical thinking (Lee and Jung, 2020; Lupetti and Van Mechelen, 2022), or trigger social interactions in the context of the city (Hoggenmueller et al., 2020b; Lee et al., 2020; Bu et al., 2023; Yamaji et al., 2010). Many of these robotic artefacts are intentionally designed to be open-ended in terms of their form factor and interactions, aiming to foster exploration and self-directed play.

On the other hand, a more structured approach to play encompasses the use of social robots as players or facilitators in games (Lupetti et al., 2018; Lupetti, 2016; Zaga et al., 2016), thereby adhering to specific rules and objectives. Lupetti et al. (2018), for example, designed and evaluated a mixed-reality playground in which children can play physical games with or against a robot. Furthermore, there have been examples where gameful design elements and principles have been applied to social robots that are deployed in a non-game context, such as education (Donnermann et al., 2021; Chen et al., 2023; Riedmann et al., 2022), labour (Chowdhury et al., 2021; Venås et al., 2024), and healthcare (Feingold-Polak et al., 2021). In addition, game elements have been used in robots to promote positive behaviour change in public spaces, such as waste sorting (Castellano et al., 2019). In the broader interaction design community, the practice of adding gameful design elements and principles to non-game contexts is commonly also referred to as 'gamification' (Tondello, 2016). This approach leverages people's intrinsic and/or extrinsic motivation to engage in an activity due to the enjoyment of the task itself or the possibility to attaining a goal (e.g., implemented through a reward system).

While previous observation studies have reported on people's playful attitudes towards delivery robots (e.g., (Dobrosovestnova et al., 2022; Weinberg et al., 2023; Pelikan et al., 2024)) and design researchers have documented case studies of urban robotic artefacts designed solely for play (Hoggenmüller et al., 2021a), there is a gap on leveraging playful engagement through gameful design to encourage casual bystanders to assist urban robots in situations of failure. Importantly, our research contrasts with most existing implementations of gameful design in HRI, which primarily use robots to engage users in a full game in order to support higher-level goals. Instead, we are investigating whether and how gameful design can be used in specific interaction scenarios (e.g., robot failure), with the robot pursuing its own primary function (e.g., delivery).

7.4.4 Summary

In summary, robots operating in urban environments will inevitably encounter situations that exceed their inherent capabilities, necessitating bystander assistance. The involvement of bystanders and the complexity of contextual factors set these casual collaborations apart from traditional human-robot collaborations. This distinction highlights the need for design investigation into strategies that can effectively facilitate such help-seeking in dynamic and unpredictable urban settings. Drawing inspiration from playful robots and the use of gameful design elements in robotics to achieve certain goals, we propose 'helping-as-play,' a novel strategy that likens robot help-seeking to playful interactions.

7.5 Design Concept Development

In our prior research (Yu et al., 2024b) on encouraging bystander assistance for urban robots, playfulness was identified as a key incentive for fostering bystander help. Building upon these findings, this study advances the exploration of using playful engagement as a strategy for robots to seek help from bystanders. Following an iterative design process, we first conducted a design workshop with members of our research group to engage in collaborative brainstorming and receive feedback on a set of initial concepts. These insights were then incorporated into the final design concepts.

7.5.1 Help-seeking scenario

Our design investigation is contextualised in real-world scenarios in which urban robots might encounter operational difficulties. These scenarios were drawn from a comprehensive online ethnography study we previously conducted. In this study, we analysed 117 user-generated videos that captured road users' casual encounters with delivery robots on TikTok [1]. We identified three typical scenarios where an urban robot may face operational difficulties, including (1) The robot is blocked and needs people to make way for it, (2) The robot is unable to cross the road and needs people to press the traffic light button for it, and (3) The robot is stuck and needs people to push it out. We chose these varied representative scenarios because they encompass different levels of engagement required from bystanders, ranging from simply making way for the robot, to manipulating city infrastructure on the robot's behalf, and to physically pushing the robot when it gets stuck which further requires more effort. At the same time, developing and evaluating design concepts across different scenarios can help validate if the playful help-seeking strategy applies to a broad range of situations that robots may encounter in urban environments.

[1] https://www.tiktok.com/

7.5.2 Design workshop

The workshop involved five members of our research group (two interaction designers, two engineers, and one urban geographer). It started with a screening of selected TikTok videos, showcasing typical challenges urban robots may face, selected from the dataset of our prior online ethnography study. This provided the workshop participants with a contextual understanding of the scenarios where robots seek assistance. Subsequently, participants were provided with paper representations of the scenarios (see Fig. 7.1 Right) to facilitate brainstorming and idea sketching. They were encouraged to incorporate game-inspired elements with specific rules to promote helping behaviours among bystanders. This focus was chosen over more open-ended playful interactions, as urban robots are functionally oriented and such unstructured interactions could potentially interfere with their operations. Following the sketching session, all participants presented and commented on each design idea, including the initial design concepts developed by the first author before the workshop.

The ideation session and discussion were consolidated into two key considerations: (1) drawing inspiration from well-known games to ensure intuitiveness in engaging bystanders, and (2) using digital content (i.e. projections) to augment elements in the urban environment. For example, in one of the design ideas generated during the workshop, a traffic light button was reimagined as part of a shooting game (see Fig. 7.1 Right). Pedestrians would press it to launch a projectile to break a 'brick wall' that blocked the robot's path. (3) Given the functionality-oriented purpose of urban robots operating in urban environments, we decided to make minimal alterations to the robots themselves (e.g., adding lights, transformations). This approach also ensures the applicability of our design concepts across various types of robots.

7.5.3 Design Concepts

Building on the ideas and insights generated from the workshop, we further developed final design concepts for robot help-seeking across the three scenarios. For each concept, we drew inspiration from a classic game, utilising its game mechanics to foster an intuitive understanding of the scenarios, motivate bystanders to assist the robot, and elicit interaction.

Scenario A: Robot blocked. In this scenario, we incorporated mechanics reminiscent of the retro game 'Tetris'. We also drew inspiration from an existing research prototype, TetraBIN, which employed similar game mechanics to encourage people

Fig. 7.1.: The design process. Left: Initial sketches with bubble-blasting (top) and PacMan (bottom) style game elements for promoting helpful behaviours. Middle: Photo from the design workshop brainstorming session. Right: Example sketch generated during the workshop, which was sketched on printed a bird's-eye view illustration of the scenario including the robot, bystanders, and text descriptions.

to deposit rubbish into a bin, thereby controlling light blocks on an integrated screen to complete the game (Tomitsch, 2014; Hoggenmueller et al., 2018). A block is projected in front of the bystander, requiring them to move to control and align the block with a corresponding Tetris-like shape projected in front of the robot (see Fig.7.2 Top). Once the block and shape match, the block 'drops' from the bystander side towards the robot, completing the Tetris line. This action destroys the line in the game, simultaneously creating enough space for the robot to pass through.

Scenario B: Traffic light button. To motivate passersby to press the traffic light button for the robot, we transformed this button into a trigger for a projected shooting game, reminiscent of classic arcade games like 'Space Invader' (see Fig.7.2 Middle). A virtual projectile was projected in front of the robot, continuously rotating to aim at 'enemies', accompanied by a projected arrow pointing at the traffic light pole. This arrow serves as an indicator, prompting passersby to press the button. When the robot's perception system detects this button-pressing behaviour, it boosts the projectile, enabling the robot to shoot 'enemies'.

Scenario C: Robot stuck. We incorporated mechanics reminiscent of the classic game 'Pac-Man', where players collect items to earn points or chase 'ghosts' for the bonus. Specifically, we projected several 'ghost' images in the intended direction of the stuck robot and a Pac-Man image in front of it (see Fig.7.2 Bottom). The game mechanics encouraged participants to 'chase' the 'ghosts' by pushing the robot towards its intended direction, thereby simultaneously aiding the robot out of its stuck position.

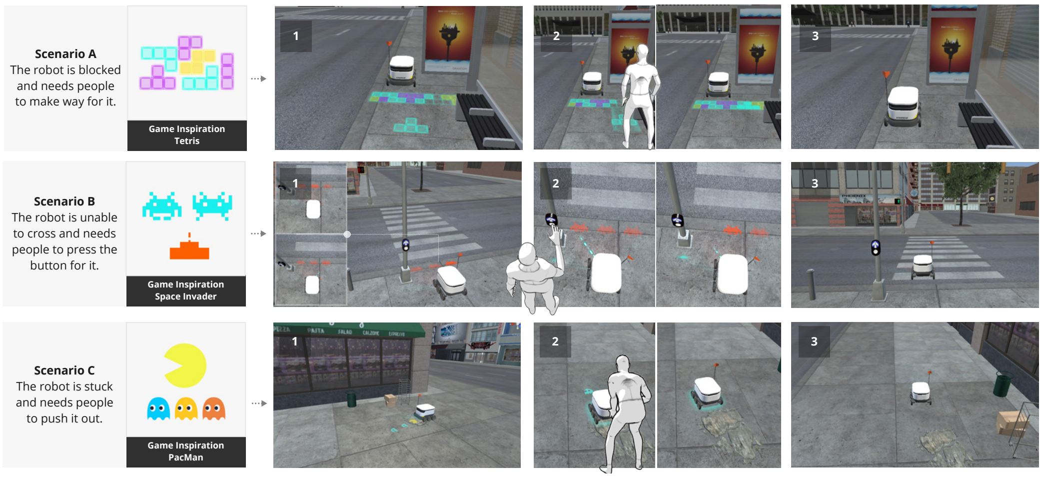

Fig. 7.2.: The design concepts. Left: Games that inspired the design concepts; Right: Illustration of the process of bystanders engaging in playful helping-seeking.

7.6 Study Design

To gain in-depth insights into our designed playful help-seeking concepts, and to explore their distinct characteristics and those of other robot help-seeking approaches that correspond to the existing perspectives of 'helping-as-work' and 'helping-as-care', we conducted a within-subject study. For 'helping-as-work', we opted for a spoken-language robot help-seeking request as previously tested in work environments for task-oriented assistance (Srinivasan and Takayama, 2016; Budde et al., 2018). For 'helping-as-care', we decided on emotional expression as robot help-seeking approach, emphasising the affective and relational aspects of interaction, previously tested in (Backhaus et al., 2018; Zhou and Tian, 2020; Urakami, 2023).

We decided on an evaluation study in VR that allows participants to experience encounters with and help-seeking requests from a delivery robot in a simulated urban space. VR simulations, now widely used for prototyping and evaluating interactions with robots (Yu et al., 2023; Milde et al., 2023; Grzeskowiak et al., 2020; Legler et al., 2023), have been validated for reproducing authentic interaction experiences Villani et al., 2018; Hoggenmüller et al., 2021b. Our study focuses on unpredictable scenarios involving urban robots needing assistance, which are difficult to replicate in public spaces. Moreover, conducting the study in VR not only minimises potential risks to participants but also reduces both the implementation time and costs associated with real-world prototypes, thus facilitating a more efficient evaluation method in design research.

Our study is specifically guided by the following research questions:

- *RQ1: How do different robot help-seeking strategies vary in terms of (1) unambiguity, (2) politeness, (3) appropriateness, and (4) effectiveness?*
- *RQ2: How do different robot help-seeking strategies affect the mood and user experience of bystanders?*
- *RQ3: How do different robot help-seeking strategies influence bystanders' attitudes towards the robot in terms of (1) acceptance, (2) trust, (3) perceived social attributes, and (4) likability?*

7.6.1 Experiment conditions

In order to compare our playful help-seeking concepts with existing strategies, we conducted a comparative study with three conditions. The conditions mapped respectively to our proposed 'helping-as-play,' and the existing strategies 'helping-as-work' and 'helping-as-care.' In the *Play* condition, we implemented our final design concepts for playful robot help-seeking (introduced in Section 3.3, see Fig. 7.2). It is worth noting that our primary objective is to compare these strategies on a conceptual level rather than specific attributes that manifest them, such as audio or visual modalities.

For the *Work* condition, we aligned the verbal help-seeking approach with 'helping-as-work' strategy, as it is commonly employed in the context of human-robot teamwork (Knepper et al., 2015; Srinivasan and Takayama, 2016; Budde et al., 2018). To compose the verbal help-seeking content, we followed the structure of *Justification* (i.e., interpreting the situation regarding the help needed) + *Introduction* (i.e., communicating a definitive instruction on how an individual should provide help) as proposed in (Budde et al., 2018) and has also been employed in the setting where a delivery robot asks bystanders for help (Boos et al., 2022) (see Table 7.1 for detail request content). The robot's help request was recorded using the 'Alex' voice of the macOS text-to-speech engine, as per the method in (Srinivasan and Takayama, 2016).

In the *Care* condition, we aligned emotional expression help-seeking with 'helping-as-care' strategy due to its effectiveness in eliciting human empathy, thus encouraging assistive behaviours (Backhaus et al., 2018; Zhou and Tian, 2020; Urakami, 2023; Daly et al., 2020). We implemented sad facial expressions, as existing research suggests that robots displaying sad emotional expressions can elicit an increased willingness to help from people (Grinten et al., 2020; Dobrosovestnova and Reinboth, 2023; Herdel et al., 2021). We used the same sad facial expression as in (Herdel

Tab. 7.1.: Speech help-seeking in each scenario

Scenario	Introduction	Justification
A: Robot Blocked	Please let me pass	I am going to be late
B: Traffic Light	Please help me press the traffic light button	I can't reach it
C: Robot Stuck	Please push me out of this spot	I am stuck

et al., 2021), because of its proven effectiveness in eliciting prosocial responses from bystanders in similar casual encounter settings. Following their approach, we created a set of faces as key-frames (See example key-frames in Fig. 7.3) and blended them into an animation sequence.

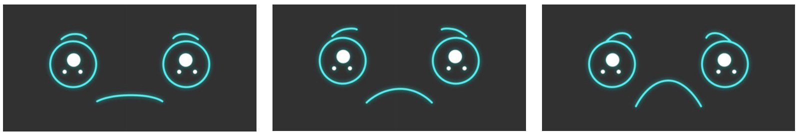

Fig. 7.3.: Key frames of robot facial expression

7.6.2 Study apparatus and implementation

We simulated the three scenarios in Virtual Reality using Unity3D[2], implementing the three different help-seeking strategies for a delivery robot for each scenario. We used off-the-shelf 3D models from the Unity Asset Store to construct scenarios, such as sidewalks and pedestrian crossings with traffic lights. For the mobile robot, we used a 3D model of the delivery robot Starship, obtained from the modeling platform Sketch Fab[3]. We employed the HTC Vive headset[4] for participants to engage in the various robot help-seeking scenarios. This setup enabled them to move freely within a 3m x 3m tracked area and interact with the virtual objects (e.g., traffic light button, robot) using simulated hands by holding the controllers.

7.6.3 Participants

We recruited a total of 24 participants in the age range of 18 to 74 years. The majority (n=17) were between 25 and 34 years old, with three aged 35-44 and two

[2]https://unity.com/
[3]https://sketchfab.com/
[4]https://www.vive.com/

aged 18-24. Our participant cohort also included two representatives from older demographics, including one participant each from the age groups of 55-64 and 65-74, respectively. Thirteen of our participants self-identified as female, ten as male, and one preferred not to disclose their gender. Participants were recruited from our university's mailing lists, flyers and social networks. All participants voluntarily took part in the experiment and initial contact had to be made by them, following the study protocol approved by our university's human research ethics committee.

7.6.4 Procedure

After participants arrived at the study site, they were first given a brief introduction about the study background and procedure. They were then asked to sign a consent form, followed by a demographic questionnaire that obtained their basic information, including age group, gender, occupation, nationality, and previous experience with AR/VR and robots. Following this, we briefly introduced the VR headset and its basic operations, and notified participants that the HMD VR was used to simulate the experience of interacting with urban robots.

Before the experiment commenced, each participant went through a familiarisation session to practice walking and interacting with the controllers in the VR environment (i.e., push a rack on wheels). We ensured that participants did not experience motion sickness and were willing to proceed with the study. By the end of the familiarisation session, participants were asked to fill out a single-item questionnaire that measured their mood.

During the experiment, each participant experienced the three experimental conditions in a different order (counterbalanced using a balanced Latin Square design which one condition precedes another exactly twice Bradley, 1958) to minimise carryover effects. Each experimental condition encompassed all three introduced scenarios: *Robot blocked*, where the robot is blocked by participants and needs them to make way for it; *Traffic light*, where the robot requires participants to press the traffic light button for it; and *Robot stuck*, where the robot is immobilised and needs participants to help it out of its stuck position. The order in which each participant experienced the scenarios was also randomised.

Before each scenario, participants were provided with a context to aid their immersion, such as waiting for a bus at a bus station. Participants were not informed about the robot's intention to seek help before the study; they were simply instructed to respond spontaneously to any cues from the robot. This aimed to reduce any sense of obligation to assist the robot resulting from the study's purpose. Each scenario concluded with participants either providing help to the robot or indicating their refusal to engage in further interaction. Subsequent to each scenario, participants filled out two single-item questionnaires that measured their mood and willingness to assist the robot through an in-headset interface. Upon completing all three scenarios within each condition, participants removed the headset and were requested to fill out several standardised questionnaires that assessed help-seeking quality, user experience, and their perceptions of the robot. After participants completed all three conditions, we conducted a post-study semi-structured interview to gain in-depth insights into their experiences. The whole study took approximately 60 minutes.

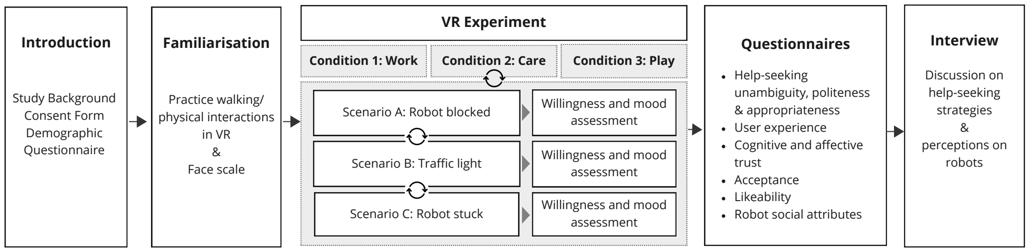

Fig. 7.4.: Study procedure

7.6.5 Data Collection

We collected both quantitative and qualitative data through questionnaires, observations, and interviews, following a mixed-methods approach (Creswell, 2014). The data collection was structured to address each of the three research questions correspondingly.

Help-seeking quality: To assess the quality of help-seeking strategies, we used items from previous HRI studies investigating robot help-seeking to measure the perceived ambiguity, politeness (Budde et al., 2018) and appropriateness (Srinivasan and Takayama, 2016). In addition, we assessed participants' willingness to help the robot after each scenario using the same item as in (Budde et al., 2018). Each dimension was rated on a 7-point Likert scale ranging from 1 to 7.

Experience and mood: To measure participants' experience of their interaction with the urban robot within the simulated VR environment, we used the short version of the widely adopted User Experience Questionnaire (UEQ-S) (Schrepp et al., 2017) on a 7-stage scale from -3 to +3. Helper's high refers to the phenomenon that helping someone or something else can lead to psychological benefits such as mood improvement (Kwak et al., 2018). To investigate its relevance in the context of helping public space robots, we also assessed participants' moods before the study and after each scenario. We used the face scale developed by (Lorish and Maisiak, 1986), which was previously used in another HRI study (Chirapornchai et al., 2021) to evaluate mood changes after helping a robot. The scale features faces numbered 1 to 20 in descending mood order, with 1 indicating the most positive and 20 the most negative mood. It is worth noting that mood assessment results from instances where participants did not offer help were excluded from our analysis, as our focus was on assessing mood changes after helping behaviour.

Attitudes towards the robot: We used the Robotic Social Attributes Scale (RoSAS) (Carpinella et al., 2017) to measure participants' perceptions of the robot, which comprises three factors: warmth, competence, and discomfort. In addition, we used the likeability subscale from the Godspeed Questionnaire (Bartneck et al., 2009b) to measure the perceived likeability of robots. For evaluating trust, we utilised the trust scale developed by McAllister (1995), which has been employed in assessing human trust towards robots (Zieger et al., 2023). This scale consists of two subscales: cognitive trust and affective trust. We selected this scale over other trust scales (Jian et al., 2000; Malle and Ullman, 2023) as its two subscales help differentiate the effects of help-seeking strategies for two types of trust: trust based on rational assessment of the robot's capabilities and trust based on emotional connections to the robot. This differentiation allows for a more nuanced understanding of how various help-seeking strategies influence trust-building between bystanders and robots. Lastly, to assess the impact of robot help-seeking strategies on participants' acceptance towards urban robots, the System Acceptance Scale developed by Van Der Laan et al. (1997) was used. Each measurement was rated on a 7-point Likert scale ranging from 1 to 7.

Semi-structured interviews: Following each experimental condition, participants were asked to provide brief feedback on their experiences in the scenarios, including their reasons for deciding to assist or not assist the robot. After finishing all experimental conditions, we conducted a semi-structured interview with participants regarding their preferences for and opinions on the different strategies and design concepts. The aim was to gain an in-depth understanding of how the various strategies influenced their willingness to offer help and shaped their overall perceptions of the robots.

7.6.6 Data Analysis

Questionnaires: We first assessed the internal reliability of all multi-item scales by calculating Cronbach's alpha. The internal reliability for the help-seeking assessments of *unambiguity* (α=0.864) and *appropriateness* (α=0.804) was found to be good. The UEQ-S scales showed good reliability for *pragmatic* quality (α=0.815) and excellent reliability for *hedonic* quality (α=0.928). The system acceptance scale demonstrated excellent reliability with α=0.918. For the RoSAS, the *competence* and *warmth* subscales showed good (α=0.899) and excellent (α=0.900) reliability, respectively, while the *discomfort* subscale had acceptable reliability of α=0.771. Lastly, the likability assessment of the robot received excellent reliability with an α value of 0.948.

We then proceeded to conduct descriptive and inferential analyses of the questionnaire data. Given the non-parametric nature of the data, we used the Friedman test to identify any statistically significant differences. In cases where significant differences were found, we performed pairwise comparisons with Bonferroni corrections. A p-value of less than 0.05 was considered indicative of a significant effect.

Interviews: All interviews were transcribed by the first author, employing a mixed thematic analysis approach (Braun and Clarke, 2006). First, all interviews were coded inductively and initial codes were sorted into sub-themes. The sub-themes were then deductively grouped into final themes, structured around the three main aspects of our research questions, aligning with the Results section's organisation.

7.7 Results

7.7.1 Received help

In our study, each participant experienced nine instances of help-seeking (3 conditions x 3 scenarios), totaling 216 help-seeking instances. The robot received help in the majority of these instances. Exceptions where participants refused to help were few: In *'Work'* condition, p18 and p8 did not help in two instances where the robot got stuck, due to the required physical effort to push the robot. In *'Care'* condition, p10, p4, and p17 did not assist in three instances, with two involving a stuck robot and one in the traffic light button scenario. In *'Play'*, p1 did not provide assistance in two cases, one with the robot stuck and another involving pressing the traffic light button. The lack of assistance in both the *'Care'* and *'Play'* conditions was attributed to participants not fully understanding the robot's help request.

7.7.2 Help-seeking assessments: unambiguity, politeness, appropriateness, and effectiveness

Quantitative results

In the descriptive analysis (see Fig. 7.5), help-seeking unambiguity was highest in the *Work*, whereas assessments of politeness and appropriateness were notably the lowest in the same condition. *Care* and *Play* showed similar levels of unambiguity, with *Play* receiving the highest scores in both politeness and appropriateness. Friedman's ANOVA revealed significant differences in both unambiguity ($\chi^2(3)$=27.179, p<0.001) and politeness ($\chi^2(3)$=6.659, p=0.036), but not in appropriateness ($\chi^2(3)$=5.37, p=0.068). Post-hoc tests revealed that *Work* received significantly higher unambiguity ratings compared to both *Care* ($p < 0.001$) and *Play* ($p < 0.001$), with no significant differences between *Care* and *Play*. Conversely, participants' politeness ratings in *Work* were significantly lower than in *Care* ($p = 0.04$) and *Play* ($p = 0.002$), with *Play* further exhibiting a significantly higher politeness score than *Care* ($p = 0.03$).

Participants' willingness to help the robot was highest in *Play*, and was lowest in *Work*. Friedman's ANOVA revealed significant differences ($\chi^2(3)$=8.47, p=0.015). Subsequent post-hoc tests revealed a significant increase in willingness to help only when comparing *Play* to *Work* ($p = 0.004$). We further analysed participants' willingness to help the robot across different scenarios. The results showed that the willingness ranking remained consistent with the overall assessment for both the robot stuck and traffic light scenarios. However, in the robot block scenario, willingness to help was slightly higher in *Care* than in *Play*. Friedman's ANOVA revealed significant differences only in the robot stuck scenario, which requires the most physical effort for participants to push the robot out of the stuck, ($\chi^2(3)$=7.136, p=0.028). Post-hoc tests revealed that participants exhibited a significantly higher willingness to help the robot in *Play* compared to both *Care* ($p = 0.03$) and *Work* ($p = 0.002$), with *Care* also demonstrating significantly higher willingness than *Work* ($p = 0.03$).

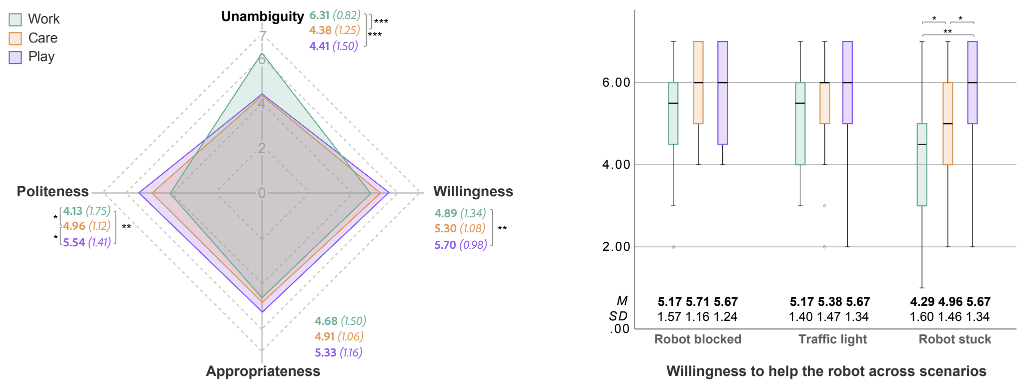

Fig. 7.5.: Qualitative assessment of help-seeking strategy (Left), Box plot of participants' Willingness to Help the robot across each scenario (Right). M: Mean, SD: Standard Deviations, *: p < .05, **: p < .01, ***: p < .001

Qualitative feedback on help-seeking quality

Unambiguity: Most participants (n=21) perceived verbal help-seeking as clear and straightforward, while some considered the helping-seeking strategies used in *Care* (n=10) and in *Play* (n=12) as lacking in unambiguity, thus necessitating closer observation of the situation to understand the robot's requests (n=7). The unambiguity and efficiency of speech communication were indicated by five participants as the primary reason for rating verbal help-seeking as their most preferred strategy. Seven participants also found the playful help-seeking approach easy to understand. Some attributed this to recognising the game from which the help-seeking originated (n=3), while others mentioned cues from the visualisation that helped infer the robot's intention (n=7), such as the 'Pac-Man' projection indicating the robot's intended direction. P7, who belonged to the older age group of over 65 and was not acquainted with some of the games, managed to engage successfully, albeit after a brief period of contemplation, as expressed in their remark, *'it did take me a minute to think'*. This learning curve in grasping the help-seeking request was also mentioned by the other nine participants, with seven of them stating that their comprehension was developing during the interactive process, such as seeing *'projections, kind of responding to my movements.'* (p12)

Regarding emotional help-seeking, nine participants easily inferred the robot's need for help from its sad face, yet were unsure of the specific assistance required, as p3 highlighted: *'[...] you know that it needs help, but it's not clear that it wants to cross the road and it wants you to press the button.'* Furthermore, participants indicated several instances of misunderstanding in both *Care* (n=4) and *Play* (n=7) conditions. For instance, some misconstrued the projection in *Play* as merely *'advertisements'* (p5, p13), while others misinterpreted the robot's sad facial expression as being *'out of battery'* (p4) or *'malfunctioning'* (p5).

Politeness: Rudeness and impoliteness were prominent in participants' comments about verbal help-seeking (n=16), with p3 and p8 notably exclaiming *'How rude!'* immediately after hearing the robot's request during the study. This aversion impression can be attributed to participants' perception of verbal help-seeking as resembling '*commands*' (n=8), being *'demanding'* (n=3), or giving them the feeling of being '*ordered around*' (n=6). The impression of an authoritative directive further led seven participants to express that they were not helping the robot out of their own will but felt obligated and even having a feeling of being *'forced'* (p2, p9, p11). P16's statement exemplified this sentiment: 'I still feel like I have to help it even though I didn't like helping it as much. [...] being given the instruction, it almost feels like you have to help it, kind of thing.' P11 even expressed concern that the robot might harm them if they did not comply with its requests, stating, 'Maybe if I did not follow the sound commands, it would hurt me.' In contrast, participants commented that *Care* (n=4) and *Play* (n=3) help-seeking strategies were less assertive and demanding. This perception could stem from the feeling that they have an option not to engage if they lack interest in these two conditions (n=9). For instance, as p1 indicated, *'If you don't have the desire to help, you can just walk away. [...] It's not demanding you to do anything.'*

Appropriateness: Furthermore, five participants found the robot's verbal help-seeking abrupt or unexpected, as p5 indicated:*'I was a bit surprised when it first spoke to me [...] you wouldn't expect a robot to randomly ask a stranger for help.* While the verbal help-seeking approach is direct, it was also perceived as interruptive by four participants. In contrast, the more implicit, playful strategies (n=6) and emotional expressions (n=2), though lacking unambiguity, were deemed less invasive and less likely to cause interruptions.

Five participants expressed feelings of aversion towards the robot verbally asking for help. P14 highlighted this sentiment: *'I feel like it is blaming me for being in his way'*. Four participants conveyed their discomfort with the robot displaying negative emotions in the *'Care'* condition. This sentiment was echoed by p17, who stated, *'I don't think anyone should be responsible for their [the robots'] personal negative energy.'* Moreover, P17 elaborated that their decision to help the robot was because they *'just wanted to finish this [the interaction]. I don't want to see that sad face.'*

Willingness to help the robot For the factors motivating participants, eleven participants expressed a neutral sentiment in *Work* condition. They did not cite specific reasons for their willingness to help, suggesting it was a natural response for them, especially if it didn't require *'too much effort'* (p1) or if they were not *'in a rush.'*(p7, p17) In the *Care* condition, the predominant factor motivating participants to offer help was the empathy evoked by the robot's sad face, as indicated by nine participants. Regarding the playful strategies, four participants indicated that the projections sparked their curiosity to engage further. This intrigue was indicated by p18, who expressed the intention to *'take on a challenge'* and *'to see if I could work it out'*. Furthermore, some participants also raised concerns about the effectiveness of help-seeking strategies for long-term deployment. Four participants indicated that they might not help the robot again in the *Work* scenario if they encountered it frequently in their daily lives. As p3 noted, they could *'accept it (verbal help-seeking) [...] if it's a one-time or two-time thing,'* but would be reluctant to offer help if they 'encounter this every day on the road'. Conversely, four participants indicated their willingness to assist the robot again if it used playful help-seeking strategies, as p9 noted it made them *'delighted and more willing to help again'*.

It is noteworthy that in scenarios where the robot was stuck and needed people to push it, six participants reported a decreased willingness to help due to the increased physical effort involved. However, p14 and p21 highlighted that the playful strategies helped to mitigate the perceived exertion involved in assisting the robot, as p14 suggested: *' distracting me from the process of helping it'*. This observation aligns with quantitative results, showing that participants' enhanced willingness to help robots in the *Play* condition was more pronounced in the robot stuck scenario than in scenarios requiring less physical involvement (See Fig. 7.5, Right).

7.7.3 Participant experience and mood change

Quantitative Results

Descriptive data analysis (see Fig. 7.6) of UEQ ratings revealed *Work* as highest in pragmatic but lowest in hedonic quality, with *Play* exhibiting the inverse pattern. Friedman's ANOVA showed significant differences in both pragmatic ($\chi^2(3)$=8.25, p=0.016) and hedonic quality ($\chi^2(3)$=16.795, p<0.001). Post-hoc tests revealed that *Work* received significantly higher ratings for pragmatic quality than both *Care* ($p < 0.001$) and *Play* ($p = 0.03$), with no significant differences between *Care* and *Play*. Hedonic ratings were significantly higher in *Play* compared to both *Work* ($p < 0.001$) and *Care* ($p = 0.0013$), with *Care* also scoring significantly higher than *Work* ($p = 0.03$).

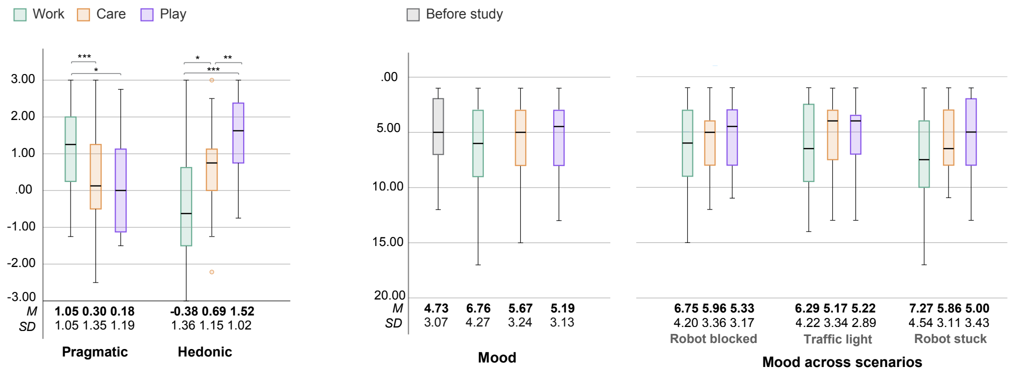

Fig. 7.6.: Box plot of UEQ results (Left), and mood assessment before and after each scenario (Right) M: Mean, SD: Standard Deviations, *: $p < .05$, **: $p < .01$, ***: $p < .001$

Participants reported better mood levels before the experiment than after assisting the robot in all three conditions, with the worst mood assessment after assisting the robot in the *Work* condition. Participants' moods after helping the robot in different scenarios showed similar patterns to the overall mood assessment, with *work* consistently rated the worst across all three scenarios. *Play* was rated higher than *Care* in robot stuck and robot block scenarios, but slightly lower in the robot traffic light scenario. Friedman's ANOVA showed no significant differences in the overall mood assessment, nor in comparisons within each scenario.

Qualitative feedback:

In the *Work* condition, participants generally appreciated the efficiency of the speech strategies used for requesting help (n=16), even though it's *'less interesting'* compared to the other two approaches (n=5). Four participants reported a neutral feeling after helping the robot, with P1 indicating, *'It feels like I'm just fulfilling a task, like doing a job'*. Two participants found speech help-seeking 'less rewarding' compared to the other two methods, and five participants reported feeling unpleasant after assisting the robot. For example, p21 described a decline in mood after helping the verbally help-seeking robot, stating their *'mood went down'* after having to repeatedly help the robot three times. Five participants attributed their neutral or unhappy feelings to the robot's lack of response after assistance. P14 exemplified this sentiment: *'I was expecting it to say thank you or something like that, but it doesn't provide any feedback, which makes me a bit unhappy'*. Furthermore, six participants expressed concerns about the accessibility of the auditory help-seeking approach, worrying that it might not be heard in noisy urban environments or by people wearing headsets.

For the *Care* condition, eight participants reported positive feelings after assisting the robot. Four of these participants noted that their positive response was similar to the feeling of helping other people or small animals in need. P20 encapsulated this sentiment: *'I would say that I felt the best when I helped the one with the sad face because it felt like I was, [...] helping out a person, almost.'* However, due to the robot's human or animal-like expressions, more participants – compared to the *Work* condition – expected a response (n=9) or wished for more interactions with the robot (n=3). For example, some participants expressed a wish to see positive reactions, such as a smiling face (n=5) or behaviours indicating excitement, like a *'dance to show some excitement'* as described by p17. Five participants reported negative feelings due to the lack of response from the robot after assisting it. Furthermore, five participants noted difficulties in seeing the robot's face when standing at the side of the robot or when pushing the robot from behind, factors which could negatively impact their experience.

Participants generally feel that their experience of helping the robot in *Play* was *'fun'* (n=8), *'enjoyable* (n=8), and *'interesting'* (n=6). Additionally, two participants expressed excitement due to the novelty of the approach. However, p14 also noted that the sense of *'freshness will disappear'* with long-term deployment. Furthermore, in the *Play* condition, half of the participants expressed a *'sense of accomplishment'* or achievement following their assistance to the robot. This feeling was exemplified by p15, who reflected, *'I felt more fulfilled, like, oh, I did something.'* Six participants noted a disconnect between game-playing and assisting a robot, with p16 describing it as *'more like having a game with the robot rather than helping it.* Furthermore, five participants highlighted the additional enjoyment that such games could bring to urban life, thus *'adding colour to the city'* (p6). Another participant, p10, suggested that they would like to see more of these types of games, as they provide a good way *'to kill the time [...] while waiting for the bus'*.

The most common negative feedback regarding the playful help-seeking experience centred on the extra effort required beyond simply assisting the robot (n=8). For example, in the traffic light scenario where participants were invited to press the button multiple times to complete a shooting game, four participants questioned the necessity of repeatedly pressing the button to complete the game. Additionally, five participants expressed a desire to skip the game and help the robot directly.

7.7.4 Attitudes towards the robot: acceptance, trust, and social attributes

Quantitative results

Following descriptive data analysis (see Fig. 7.7), participants' acceptance of the robot was highest in *Play* and lowest in *Work*. Friedman's ANOVA showed significant differences ($\chi^2(3)$=9.156, p=0.01). Post-hoc tests indicated the acceptance scores in both *Play* ($p = 0.001$) and *Care* **(**$p = 0.04$**)** were significantly higher than in *Work*, with no significant differences between *Care* and *Play*.

Regarding the robot's social attributes, it received the lowest competence rating in *Care* and the highest in *Play*. The robot's warmth attributes received the highest rating in *Care*, slightly lower in *Play*, and the lowest in *Work*. The robot received the lowest discomfort rating in *Care* and the highest in *Work*. Significant differences were found in Friedman's ANOVA test across all three dimensions (competence: $\chi^2(3)$=12.413, p=0.002; warmth: $\chi^2(3)$=13.130, p=0.001; discomfort: $\chi^2(3)$=13.505, p=0.001). Post-hoc tests indicated that the robot was rated significantly less competent in *Care* compared to both *Work* ($p = 0.01$) and *Play* ($p = 0.001$), with *Play* also scoring significantly higher than *Work* ($p = 0.01$). Warmth ratings were significantly higher in both *Care* ($p = 0.001$) and *Play* ($p < 0.001$) compared to *Work*, with no significant differences between *Care* ($p = 0.03$) and *Play*. Robots in both *Care* ($p < 0.001$) and *Play* ($p = 0.006$) were rated significantly lower for discomfort than those in *Work*, and *Care* also scoring significantly lower than *Play* ($p = 0.03$).

Participants' trust was highest in *Play* and lowest in *Work* across both cognitive trust and affective trust subscales. *Care* received the lowest cognitive trust rating, while *Work* received the lowest affective trust rating. Friedman's ANOVA showed significant differences in cognitive trust ($\chi^2(3)$=7.670, p=0.022), but not in affective trust ($\chi^2(3)$=5.365, p=0.068) subscales. Post-hoc tests revealed that participants' cognitive trust ratings in *Play* were significantly higher than in *Work* ($p = 0.01$) and *Care* ($p = 0.001$). There were no significant differences between *Care* and *Work* in the cognitive trust subscale.

At last, the robot in *Work* was rated lowest in likability, followed by *Care* and *Play*. Friedman's ANOVA showed significant differences ($\chi^2(3)$=15.438, p<0.001). Post-hoc tests indicated the likability scores in both *Play* ($p = 0.001$) and *Care* **(**$p = 0.001$**)** were significantly higher than in *Work*, with no significant differences between *Care* and *Play*.

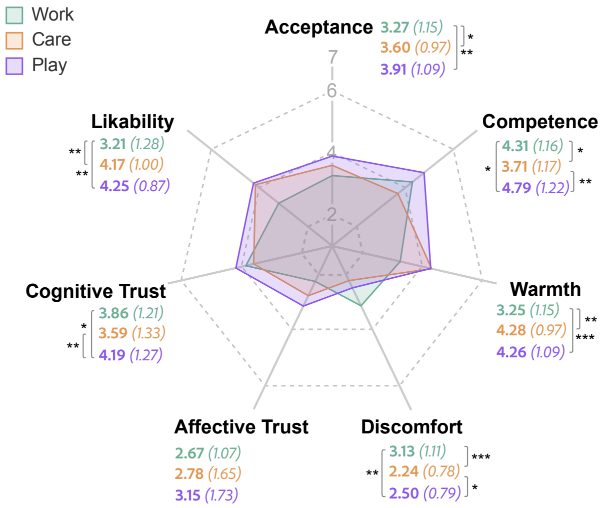

Fig. 7.7.: Qualitative results of participants' attitudes towards the robot. *: $p < .05$, **: $p < .01$, ***: $p < .001$

Qualitative feedback on impressions of the robot

The synthesised voice in *Work* condition was perceived by six participants as machine-like or artificial. Three participants mentioned that the speech functionality aligned with their expectations of a robot, leading them to perceive the robot as *'competitive'* (p14) and *'professional'* (p17), while on the other hand three participants described the robot as *'scary'* or *'creepy'*.

In the *Care* condition, *'cute'* was the impression most frequently attributed to the robot by participants (n=9). Additionally, we observed that two participants petted the robot upon their first encounter, as exemplified by p1, who expressed a desire to comfort it due to its sad facial expression. Many participants also indicated that the facial expression made the robot more human-like (n=7) or animal-like (n=6). However, the sad emotion also raised people's questions towards the robot's capability (n=6), making it less trustworthy (n=5) or even *'stupid'* (n=2). P12 exemplified this sentiment by describing the robot with the sad face as *'useless'*, likening its helplessness to the impression of *'a baby'* and commenting, *'It's like a baby, so I don't think I can trust the robot to do a lot of things.'* Furthermore, three participants felt manipulated by the robot displaying a sad face to prompt them to offer help. P3 noted, *'The one with expressions feels like it's a robot using tactics, like pretending to be pitiable.'* Another intriguing response from p1 suggested they felt somewhat *'being scammed'* for helping the robot.

In the *Play* condition, five participants described the robot as *'smart'* or *'intelligent'*. Three participants indicated that they have more confidence in the robot's problem-solving abilities. P14 further elaborated on this point, indicating that the robot appeared *'to have predicted that it would encounter such difficulties'* and was able to use a playful strategy *'to overcome a particular scenario'*. Two participants described the robot as being *'active'* (p16) and *'sociable'* (p17), noting that it consistently sought the attention of passersby to engage them in game-playing. Furthermore, while four participants perceived the robot projecting a game onto the ground as less human-like, even comparing it to a *'game console'* (P3), two other participants felt as though they were playing a game with a *'kid'*.

7.8 Discussion

The section starts with three key considerations for facilitating robot help-seeking from bystanders generated from study results, then delves into a focused reflection on the game-inspired playful help-seeking strategy.

7.8.1 Casting bystander help as voluntary engagement over obligated response

Achieving task efficiency has long been one of the primary objectives in human-robot collaboration (Ajoudani et al., 2018). Thus, verbal speech help-seeking has become the most common method for robots to express their need for assistance, due to its rich and intuitive communication, widely adopted in both research (Backhaus et al., 2018; Budde et al., 2018; Cameron et al., 2015; Knepper et al., 2015; Srinivasan and Takayama, 2016) and commercially-deployed urban robots (Mail, 2023). However, our study results raise questions about whether such explicit, direct, and objective-oriented approaches are suitable for situations where robots request help from bystanders. Despite its clarity and communication efficiency, verbal help-seeking was perceived negatively in terms of politeness and appropriateness, casting an unfavourable impression of the robot as also evidenced through the lowest levels of liking and acceptance among all tested conditions. Participants' comments revealed a conflict that emerged from their perceived role as passive bystanders without responsibility towards the robot, as opposed to the sense of command and obligation that they felt when receiving direct requests from the robot. This conflict in turn resulted in aversion and their reported reduced willingness to provide assistance.

In contrast, implicit methods such as emotional expression and playful engagement, while less efficient in terms of clear communication, were perceived as more polite and socially acceptable. For individuals who casually encounter urban robots in public spaces while being involved in a variety of activities and having different agendas, there is often a misalignment of goals with those of urban robots (Pelikan et al., 2024; Hüttenrauch and Eklundh, 2006). Consequently, it becomes crucial that when robots seek assistance from these bystanders, they do so in a manner that minimises disruption to the activities these individuals are currently engaged in. Therefore, participants generally favoured the indirect and implicit nature of emotional expression or playful help-seeking, as these approaches engendered a feeling of reduced obligation, conveying to the bystander that they have the freedom to ignore the request and opt not to assist. Urban robot help-seeking strategies should therefore consider implicit and less persuasive approaches, presenting bystander assistance as a voluntary, spontaneous act driven by personal kindness or playful interest, rather than as an obligation, which is often associated with direct verbal requests.

7.8.2 Incentivising bystander efforts through playful help-seeking strategy

Prior research suggests that more laborious requests from robots tend to reduce people's willingness to assist (Srinivasan and Takayama, 2016). Our study explored this phenomenon across three distinct help-seeking scenarios, ranging from minimal (such as stepping aside to allow the robot to pass) to such that required more physical effort (like bending over to push a stuck robot). We observed a clear trend in *Work* and *Care* conditions, where participants demonstrated a reluctance to engage in the more physically demanding task of pushing the robot. Interestingly, participants' willingness to help in *Play* conditions was consistently stable across all scenarios. Furthermore, the disparity between the playful strategy and the two other help-seeking strategies in terms of willingness to help was even more pronounced in the robot stuck scenario that had the highest request demand.

This trend was also mirrored in participants' mood changes. In *Work* and *Care* conditions, more laborious requests (i.e., in the robot stuck scenario that required participants to bend over to push the robot) led to a decrease in their mood after helping the robot. Conversely, in *Play* condition, the most effort-intensive robot stuck scenario resulted in the highest reported mood levels. Although various game-inspired concepts may have influenced the outcomes, participants primarily attributed the elevated mood levels in the effort-intensive scenarios to an increased sense of achievement and competence, which is the key motivational impact of gaming elements (Tondello, 2016). This experience effectively neutralised the perceived effort and the accompanying sense of fatigue.

Drawing upon the principles of reciprocity and altruism in social exchange theory (Cropanzano and Mitchell, 2005), our study highlights that bystanders, who do not directly benefit from urban robot services, often need a form of incentives for their time and effort in assisting robots they encounter casually. Such needs are particularly significant when the physical effort from helpers increases, highlighting the lack of direct mutual benefits. While playful help-seeking strategy, leveraging gameful experiences, offers a potential solution, using game elements as motivators could also raise ethical considerations about invisible labour (Dubbell, 2015) – a concern also noted in socio-technical research on bystander assistance for commercially deployed robots (Dobrosovestnova and Reinboth, 2023). While participants in our study generally expressed autonomy in deciding whether to engage in gameplay, it is important to be mindful of the potential for creating invisible labour when designing gameful incentives.

7.8.3 Avoiding helpless robot portrayal

Public trust and acceptance are crucial for the successful integration of robots into urban environments. There have been instances where distrust by the general public even led to regulatory bans on urban robots (Hoffmann and Prause, 2018). Despite this, the specific impact of robot help-seeking behaviour on people's attitudes towards robots has not been explored in existing research.

Previous research has shown that robots displaying sad emotions are more likely to receive human assistance, both in collaborative settings (Zhou and Tian, 2020; Urakami, 2023) and when used in robot pets seeking help (Daly et al., 2020). Our research expands upon the investigation of using emotional expressions to elicit help from bystanders, uncovering patterns that diverge from those in more traditional human-robot collaboration settings. While emotional expressions are generally effective in eliciting help in human-robot teaming (Urakami, 2023), our findings suggest that in casual bystander contexts, a robot displaying sadness was perceived as needy and less competent, which at the same time resulted in a decrease in people's cognitive trust. These expressions even further engendered a perception of emotional blackmail, especially without an established human-robot relationship between bystanders. This aligns with prior findings (Yu et al., 2024b) that bystanders tend to view urban service robots as professional entities, thereby expecting them to exhibit proficiency and dependability.

In contrast, robots employing playful strategies were perceived as more capable, as they were perceived as actively helping themselves out of situations using well-prepared and dedicated strategies. This approach further resulted in enhanced trust and acceptance towards the robot. We therefore conclude that urban robot help-seeking should avoid portraying robots as helpless or needy in order to minimise the negative impact on bystander trust in the robot.

7.8.4 Reflections on the game-inspired playful help-seeking design concepts

Our user study demonstrated that integrating mechanics and visual cues from classic games has the potential to effectively engage bystanders in playful human-robot collaborations as a means to provide assistance to a robot. Notably, this was also true for the two participants (p7 and p13) from the older demographic group. Analysis of their willingness to help results in *Play* condition revealed that neither participant was statistically deviant from the overall sample, with standard deviations of 1.352 and 0.0854, respectively. Particularly, p7, who is over 65 and was not familiar with some of the games but managed to comprehend and engage successfully. However, while most participants could recognise and comprehend the game's functions, there was some ambiguity about whether *they* were invited by the robot to participate. Noteworthy, this issue did not arise in the Tetris-inspired concept, as the movement of the tetra block in response to the participants' actions made it immediately clear that they had full control over the game elements. Conversely, in the other scenarios requiring mediation of other objects for game element manipulation (i.e. pressing the traffic light button to shoot the projectile or pushing the robot to chase the ghosts), participants faced a steeper learning curve and expressed uncertainty regarding their involvement. These findings suggest that when designing game-inspired playful help-seeking requests, game elements should be designed in a way that they respond instantly to bystander movement or incorporate a feed-forward mechanism (Nguyen et al., 2023).

Repetition is a fundamental aspect of game design, serving as a key reinforcement of game mechanics and thereby enhancing player engagement (Robson et al., 2015). Our design concepts also employed repetitive elements; for instance, bystanders were required to press the traffic light button multiple times to eliminate all enemies. While enjoyable for some participants, others noted a disconnect between the game context, requiring repetitive action, and the real-life context, where a single press of the traffic light button is typically sufficient. This feedback highlights a potential mismatch between game mechanics and real-world expectations. Furthermore, several participants indicated a preference for omitting repetitive game-play actions if they were in a rush. Considering the rapid pace of urban life, it is evident that designing for game-inspired playful help-seeking must be succinct and allow for flexibility in engagement, accommodating the varying preferences and time constraints of bystanders.

Moreover, it's crucial to consider the broader urban environment where such playful engagements for robot help-seeking are situated. The novelty effect observed in our study, if implemented in the real world, necessitates consideration of the potential impact of people crowding, as people may gather around the interaction area. Furthermore, since the game-playing interaction is attention-demanding, it could distract bystanders from cautiously observing their surrounding traffic environment, potentially leading to safety concerns. Additionally, the urban environment's rhythm, busy on workdays and relaxed on weekends, could affect bystander engagement levels. Game-inspired playful help-seeking design should thus adapt to these varying urban rhythms to better align with people's availability and willingness to engage.

7.8.5 Limitations

First, the controlled lab study design may not fully reflect spontaneous real-life helping behaviour, as some participants noted potential differences in their decisions. In addition, the scenarios included in our study could be subject to the potential bias of social media posts, as they are derived from a previous online ethnography study. Conducting field studies with real robots and naive bystanders across more diverse scenarios could further validate our findings. Second, the ecological validity of this work is limited by the use of a VR simulation. The novelty of the VR experience influenced participants' mood assessments, potentially leading to inflated mood ratings after the VR familiarisation session. This may explain why the 'helper's high' phenomenon – helping someone or something else can lead to psychological benefits – was not validated in our study. Furthermore, implementing the playful design concepts in VR overlooks potential technical challenges in real-world implementations. For instance, limitations exist in projecting in outdoor environments due to variations in lighting and distance constraints. While the VR study validates the playful help-seeking strategy as a proof of concept, further technological refinement and adaptation are required for practical real-world application. Third, our study findings are based on a small group of participants with Western cultural or educational backgrounds, which might have facilitated their understanding of such game-playing interactions. To ensure the generalisability of these findings, further validation is necessary with participants from a more diverse range of cultural backgrounds.

7.9 Conclusion

Our study extended the use case of playful engagement in HRI from creating enjoyable experiences to facilitating casual collaboration. The evaluation study in VR with 24 participants found that playful engagement has the potential to enhance bystanders' willingness to assist and improve their mood after helping the robot. In our study, this effect was particularly noticeable when the assistance required more effort. By comparing the helping-as-play strategy with helping-as-work (using verbal help-seeking) and helping-as-care (using emotional expression) strategies, we found that participants perceived verbal help-seeking to be impolite and that there was a decline in trust towards the robot when using sad emotions to request help. These findings prompt broader considerations for robot help-seeking in urban contexts and offer insights into playful help-seeking as a strategy to obtain assistance from casual bystanders in dynamic and unpredictable urban environments.

8 Feel the Presence: The Effects of Haptic Sensation on VR-Based Human-Robot Interaction

8.1 Preamble

Xinyan Yu, Marius Hoggenmüller, Tram Thi Minh Tran, Martin Tomitsch. (2025). Feel the Presence: The Effects of Haptic Sensation on VR-Based Human-Robot Interaction. In *Proceedings of the 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN '25)*.

This chapter presents a comparative study that replicated the experiment in Chapter 7, replacing the original VR setup with a simulation using haptic gloves to provide realistic tactile and force feedback. While the main focus of this chapter is to examine the role of haptic sensation in VR-based HRI studies, the evaluation of the design concept itself also partially addresses RQ3: *"How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?"*.

This chapter provides insights into the impact of haptic sensation in VR-based HRI evaluation, showing its role in enhancing participants' social and self-presence in VR and influencing their affective-related perceptions of the robot. It makes a methodological contribution by advancing knowledge on how highly realistic haptic feedback can be integrated into VR-based HRI prototypes and how it can shape study outcomes.

This chapter was originally published as a paper at the IEEE International Conference on Robot and Human Interactive Communication (RO-MAN) and is available in the IEEE proceedings of this conference. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis' standards.

8.2 Abstract

Virtual reality (VR) has been increasingly utilised as a simulation tool for human-robot interaction (HRI) studies due to its ability to facilitate fast and flexible prototyping. Despite efforts to achieve high validity in VR studies, haptic sensation, an essential sensory modality for perception and a critical factor in enhancing VR realism, is often absent from these experiments. Studying an interactive robot help-seeking scenario, we used a VR simulation with haptic gloves that provide highly realistic tactile and force feedback to examine the effects of haptic sensation on VR-based HRI. We compared participants' sense of presence and their assessments of the robot to a traditional setup using hand controllers. Our results indicate that haptic sensation enhanced participants' social and self-presence in VR and fostered more diverse and natural bodily engagement. Additionally, haptic sensations significantly influenced participants' affective-related perceptions of the robot. Our study provides insights to guide HRI researchers in building VR-based simulations that better align with their study contexts and objectives.

8.3 Introduction

The integration of robots into everyday life requires the development of effective interaction strategies, which in turn necessitates appropriate methods for prototyping and evaluation (Woods et al., 2006; Riek, 2012; Zamfirescu-Pereira et al., 2021). However, prototyping and evaluation interactions with real robots present challenges, including high development costs, potential risks to participants, and difficulties in replicating real-world contexts. To address these challenges, researchers increasingly employ virtual reality (VR) as a prototyping tool to simulate human-robot interactions (HRI) in controlled lab settings (Miner and Stansfield, 1994; Khastgir et al., 2015; Hoggenmüller et al., 2021b).

Despite its potential, ensuring the validity of a VR study is crucial to achieving reliable results that can be translated to real-world settings (Wijnen et al., 2020). While current simulation methods for HRI experiments strive to recreate realistic visual and auditory experiences (Hoggenmüller et al., 2021b), haptic sensation—one of the most important sensory modalities for perception (Srinivasan and Basdogan, 1997) that enhances VR realism (Hoffman, 1998)—is often absent from the experience. In most HRI studies, even when contact-based physical interaction strategies are tested, the study setups typically rely on hand controllers or hand tracking to facilitate these interactions (Ortenzi et al., 2022; Higgins et al., 2024), without enabling participants to experience tactile and force feedback when simulating embodied interactions with robots.

Haptic sensation has been shown to play a crucial role in shaping how people behave (Ebrahimi et al., 2016; Jacucci et al., 2024), and interact with virtual human avatars in VR during social interactions (Krogmeier et al., 2023; Bailenson et al., 2003; Venkatesan et al., 2023; Giannopoulos et al., 2008) (e.g., influencing proxemic behaviour (Bailenson et al., 2003), intensifying emotional engagement (Venkatesan et al., 2023; Ahmed et al., 2016)). However, interactions with robots differ fundamentally from those with humans due to differences in agency, embodiment, and social expectations (Fong et al., 2003). Thus, how haptic sensation impacts people's perception of robots and their interactions with them in VR remains unknown. Beyond social perception and interaction, the lack of realistic haptic simulation can also greatly limit the effectiveness of VR for evaluating a product's usability and user experience (Bruno et al., 2010). This further emphasises the importance of studying the impact of replicating haptic sensations on people's assessments of robots in VR-based studies.

Advances in haptic technology have enabled the direct touch and manipulation of computer-generated objects in VR in ways that evoke a compelling sense of tactile realness (Sreelakshmi and Subash, 2017; Caeiro-Rodríguez et al., 2021; Al-Sada et al., 2018). Industrial-grade tools such as HaptX Gloves[1] can provide high-quality haptic feedback through microfluidic technology, simulating force feedback (e.g., hardness, weight, resistance) and tactile feedback (e.g., texture, smoothness, friction) to enhance realism in virtual interactions. HaptX Gloves have been integrated into Volkswagen's vehicle design and training VR platform to support in-vehicle prototyping and evaluation (Stamer et al., 2020). In addition, a growing range of affordable and diverse commercial smart gloves has made haptic technology increasingly accessible to researchers (Caeiro-Rodríguez et al., 2021).

Building on these advancements, we explore the potential of highly realistic haptic feedback to enhance VR-based HRI experiments by incorporating HaptX Gloves into a VR setup, enabling participants to physically interact with virtual representations of robots and their surrounding environment. To examine the effects of haptic simulation using haptic gloves on participants' sense of presence and their assessments of robots, we replicated a robot help-seeking study that we previously conducted (Yu et al., 2024a). In the replication study presented here, we compared a haptic gloves setup, which provides participants with tactile and force feedback and allows them to directly interact with the virtual robot using their hands, with the original setup that

[1] https://haptx.com/

used hand controllers for interaction. Our work makes the following contributions: (1) We present a VR-based HRI study setup that incorporates highly realistic haptic gloves, enabling haptic sensations during physical interactions with virtual robots; (2) We provide empirical evidence on how such a setup influences participants' sense of presence, bodily engagement, and affective perceptions of the robot, offering practical guidance for researchers building VR-based HRI studies.

8.4 Related Work

8.4.1 VR as a prototyping tool for HRI

VR as a prototyping tool for HRI has demonstrated its ability to effectively simulate real-world human-robot interactions. For instance, Villani et al. (2018) found comparable results in task performance and evaluations when comparing interactions with real robots to those in VR within a human-robot collaborative task setting. Similarly, Sadka et al. (2020) observed that social interpretations of a non-humanoid robot's gestures in VR closely resemble those in the real world.

However, notable differences remain in how participants interact with and assess robots in VR compared to real-world settings. For instance, Wijnen et al. (2020) replicated a study by Kahn et al. (2015) on people's secret-keeping behaviour with robotic and human tour guides in VR. The replication VR study found that participants were more likely to keep secrets for the non-social robot, contradicting the original study's results. In a human-robot collaborative building task study, Higgins et al. (2024) reported that each attempt by participants to complete the task took significantly longer in VR. While this study did not directly examine the impact of haptic sensation, the authors attributed the performance differences to difficulties in depth perception in VR, a perception in which haptic sensation plays a key role (Makin et al., 2019). Despite the recognised importance of haptic sensation for enhancing VR realism, VR-based HRI studies, even those involving contact-based interactions, rely on hand controllers or hand tracking (Ortenzi et al., 2022; Higgins et al., 2024) as participant interaction method, limiting participants from experiencing tactile and force feedback with virtual robots. However, investigations into how a VR setup that enables realistic haptic sensations affects participants' behaviours and assessments of robots in VR-based HRI studies remain limited.

8.4.2 Importance of haptics in VR

Haptic sensation is essential for enhancing immersion and realism in VR environments (**Wijnand2000Presence**; Bystrom et al., 1999). To enable touch-based interactions, various devices have been developed to simulate haptic sensations, allowing users to perceive tactile and force feedback when engaging with virtual objects, with most focusing on the hands as the primary modality for interaction (Perret and Vander Poorten, 2018; Culbertson et al., 2018; Pacchierotti et al., 2017). Integrating haptic feedback into VR simulations has demonstrated benefits across multiple domains, including improving performance in VR surgical training (Gani et al., 2022), enhancing precision in fine manipulation tasks such as drawing (Richard et al., 2021), reducing execution time for tasks like throwing and stacking (Kreimeier et al., 2019), or improving the remote manipulation of robots (Brogi et al., 2024; Ni et al., 2017). Beyond task performance, haptic feedback has been shown to shape social interactions in VR, influencing how people engage with virtual human avatars (Krogmeier et al., 2023; Bailenson et al., 2003; Bailenson and Yee, 2008; Giannopoulos et al., 2008; Venkatesan et al., 2023). For example, Bailenson et al. (2003) found that participants maintain larger interpersonal distances from virtual avatars in VR compared to real-world interactions, due to the absence of tactile haptic contact with virtual representations. Haptic sensation has also been shown to enhance the sense of social presence when interacting with another human avatar in shared virtual environments (Giannopoulos et al., 2008). While these studies focus on task performance or interactions with virtual avatars of another human, the impact of haptic sensation on people's perception and behaviour toward virtual robots, given their distinct agency, embodiment, and social expectations (Fong et al., 2003), remains unknown.

8.4.3 Haptic sensation in VR-based prototyping and evaluation

VR has been widely adopted as a prototyping tool for studying interactions with interactive systems, such as robots (Miner and Stansfield, 1994), autonomous vehicles (Khastgir et al., 2015; Hoggenmüller et al., 2021b) and smart devices (Voit et al., 2019), reducing complexity, costs, and risks in development and evaluation. Previous work has shown that haptic sensation plays a critical role in facilitating effective assessments in VR-based prototyping and evaluation. Schölkopf et al. (2021) highlighted that the absence of haptic feedback severely diminishes user experience ratings, emphasising its importance for meaningful user experience assessments in VR. Similarly, Stamer et al. (2020) investigated high-fidelity haptic feedback in user

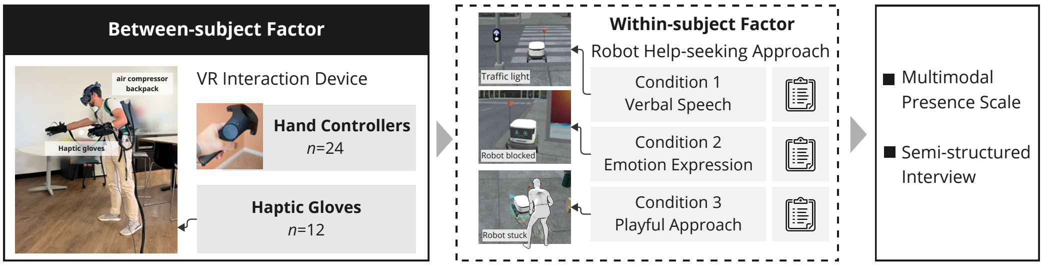

Fig. 8.1.: Study Design

in-vehicle experience evaluation and found that participants recognised interactions significantly faster and more accurately when haptic feedback was present compared to when it was absent. While these studies demonstrate the value of realistic haptic simulation in VR-based prototyping with traditional user interfaces, its role in supporting the assessment of physically and socially embodied robots remains largely unexplored.

8.5 Methodology

8.5.1 Study design

This study replicates our previous study of how urban robots that get stuck seek help from bystanders (Yu et al., 2024a). While maintaining the same study procedure and data collection methods as the original, we replaced the hand controllers in the original setup with haptic gloves to investigate the effects of haptic simulation. The interaction device (i.e., hand controllers or haptic gloves), constitutes the between-subject factor and is the primary focus of our investigation in this paper. To ensure methodological consistency with the original study, participants within each group experienced multiple robot help-seeking methods (i.e., speech, emotional expression, and playful help-seeking, see Fig. 8.1), forming the within-subject factor. For speech help-seeking, the robot emitted a voice prompt, such as *'Please help me press the traffic light button, I am going to be late.'* For emotional help-seeking, the robot displayed a sad facial expression. For playful help-seeking, the robot used an interactive ground projection inspired by games to elicit helping behaviours[2]. While these within-subject conditions are not the primary focus of this study, their inclusion maintains alignment with the design and scope of the original investigation.

[2]For more details on these help-seeking approaches, please refer to the original study (Yu et al., 2024a).

Twenty-four participants from the original study formed the *Hand Controllers* group (A1-A24, aged 18 to 74 years, with most (n=17) between 25 and 34 years), while 12 participants completed our study using haptic gloves, forming the *Haptic Gloves* group (B1-B12, aged 18 to 34 years, with most (n=8) also between 25 and 34 years). Since the primary focus of this study was on between-subject group effects rather than comparing different help-seeking methods, the help-seeking methods were treated as repeated measures, allowing us to achieve adequate statistical power with a smaller sample size.

8.5.2 Study procedure

Upon arrival, participants received a brief introduction to the study's background and procedure, followed by instructions on the VR devices and their use. Before the experiment, they went through a familiarisation session, practising walking and interacting with virtual objects in VR (e.g., pushing a rack on wheels) using either hand controllers or haptic gloves. During the experiment, participants followed the same procedure as the original study, experiencing three within-subject conditions: the robot's help-seeking methods of speech, emotional expression, and playful help-seeking, in a counterbalanced order. The study was situated in a virtual urban environment, where robots seek assistance from random pedestrians. Participants experienced each robot help-seeking methods multiple times across three scenarios (see Fig. 8.1): *Robot blocked*, where the robot is obstructed requires participants to make way; *Traffic light*, where the robot requires participants to press the traffic light button for it; and *Robot stuck*, where the robot is immobilised and depends on participants to help it out of its stuck position. Participants were not informed about the robot's intention to seek help and were instructed to respond spontaneously to its cues. After each help-seeking condition, participants removed the headset to fill out several standardised questionnaires that assessed their perceptions of the robot. Upon completing all trials, they filled out an additional questionnaire on their sense of presence in VR. We also conducted a post-study semi-structured interview to gain in-depth insights into their experiences. Each session took approximately 60 minutes.

8.5.3 Study apparatus and implementation

The VR simulation was developed in Unity3D[3] and deployed on an HTC Vive headset[4]. The experiment was conducted in a 5x5-metre open floor space, allowing participants to physically walk within the simulated urban space. Participants in the original study used the default HTC Vive controllers, while those in our *Haptic Gloves* group interacted with the virtual environment directly using HaptX Gloves (see Fig. 8.1). The HaptX Gloves used in our study provide high-fidelity tactile feedback on the fingers and palms through microfluidic actuators, which inflate and deflate to create localised pressure, simulating the texture details of virtual objects. They also provide force feedback via a mechanical resistance system that restricts finger movement to render varying levels of stiffness, allowing participants to perceive the weight and rigidity of objects in VR. The HaptX system operates via a compressed air-powered setup, consisting of an air compressor backpack weighing approximately 9 kg and a pair of gloves (see Fig. 8.1, left). The backpack supplies compressed air through pneumatic tubing, driving the actuators in the gloves to deliver real-time tactile feedback. Participants wore the backpack and gloves, allowing them to directly manipulate virtual objects with their hands and feel them as if they were physical. This setup enabled realistic interactions with all VR objects within participants' reach, including the robot (e.g., pushing the robot) and environmental elements (e.g., pressing a traffic light button).

8.5.4 Data collection

Sense of presence: Participants' sense of presence in VR was evaluated using the same Multimodal Presence Scale (MPS) (Makransky et al., 2017) from the original study, encompassing three dimensions: physical, social, and self-presence.

Perceptions of the robot: To examine how haptic sensations influence participants' assessments of the robot in VR, we evaluated their perceptions across several dimensions aligned with the original study. The Robotic Social Attributes Scale (RoSAS) (Carpinella et al., 2017) assessed participants' perceptions of the robot, including warmth, competence, and discomfort. The System Acceptance Scale (Van Der Laan et al., 1997) measured participants' acceptance towards the robot, while the likeability subscale from the Godspeed Questionnaire (Bartneck et al., 2009b) evaluated perceived likeability. Trust was measured using the trust scale (McAllister, 1995), which consists of two subscales: cognitive trust and affective trust. Lastly, the

[3] https://unity.com/
[4] https://www.vive.com/

short version of the User Experience Questionnaire (UEQ-S) (Schrepp et al., 2017) captured participants' overall user experience. All measures used a 7-point Likert scale.

Qualitative data: We took observation notes of participants' behaviours during the study. In addition, we conducted a semi-structured interview with participants after they completed all experimental tasks, during which we asked questions about their overall experience in VR and their perceptions of the robots.

8.5.5 Data analysis

Quantitative analysis: We first assessed the internal reliability of all multi-item scales by calculating Cronbach's alpha. For the MPS, physical presence showed acceptable reliability ($\alpha = 0.747$), and self presence demonstrated excellent reliability ($\alpha = 0.892$). The social presence subscale had questionable reliability ($\alpha = 0.674$). Following advice on Cronbach's alpha in Tavakol and Dennick, 2011, we removed items with correlations below 0.25 for following analysis, which improved reliability to an acceptable level ($\alpha = 0.710$). The likeability scale received excellent reliability (α=0.923). The trust scales showed excellent reliability for affective trust (α=0.930) and good reliability for cognitive trust (α=0.823). The System Acceptance Scale showed good reliability (α=0.887). For the RoSAS, competence and warmth showed good (α=0.867) and excellent (α=0.900) reliability, respectively, while discomfort had acceptable reliability (α=0.761). Lastly, the UEQ-S scales showed good reliability for pragmatic quality (α=0.806) and excellent reliability for hedonic quality (α=0.904).

To compare sense of presence between groups (hand controllers vs. haptic gloves), we conducted independent samples t-tests for each MPS subscale. Given the unequal sample sizes between groups, we assessed variance homogeneity using Levene's Test. When equal variances were violated ($p < 0.05$), Welch's t-test was applied to account for heterogeneity. Additionally, effect sizes (Cohen's d) were calculated to provide insight into the practical significance of group differences.

For participants' robot assessments, we applied a Linear Mixed Model (LMM) to account for repeated measures across the within-subject factor (Conditions, i.e., robot help-seeking approaches). The between-subject factor (Groups, i.e., hand controllers vs. haptic gloves) was specified as the primary fixed effect of interest. The interaction effect between Group and Condition was included to examine whether the impact of Conditions varied across Groups. Participants were treated as a random effect to account for inter-individual differences. The LMM calculated estimated marginal means for fixed effect and also accounted for unequal sample sizes and modelled dependencies between repeated measures using a Compound Symmetry covariance structure. Effect sizes (Cohen's d) were calculated to assess practical significance.

Interviews: We employed an inductive semantic analysis (Braun and Clarke, 2006) to identify patterns in participants' comments that could supplement our understanding of the quantitative results. Interviews were transcribed and analysed by the first author.

8.6 Results

This section begins with observations of participants' behaviours and related interview comments. We then present differences in sense of presence between groups, supported by interview insights to contextualise the results. Finally, we report statistical findings on participants' assessments of robots, including main group effects and interaction effects.

8.6.1 General observations

The robot received help at similar rates across both groups. In *Haptic Gloves* group ($3 \times 3 \times 12$ trials), help was provided in 104 trials (96.3%). In the *Hand Controllers* group ($3 \times 3 \times 24$ trials), help was provided in 209 trials (96.8%). Despite similar helping decisions, participants in *Haptic Gloves* group demonstrated more natural and diverse full-body engagement during the study, including tapping the robot with hands (n=4), using their feet to interact with it (n=3), dragging the robot's flagpole (n=2), or giving it a high-five (n=1). In contrast, these spontaneous and varied bodily engagements were rarely observed in *Hand Controllers* group, where only one instance of tapping the robot occurred.

Post-study interviews provide insights into these behavioural differences. Five participants attributed their more frequent and diverse bodily engagement to the absence of controller constraints, referencing their previous experiences using hand controllers in other VR settings. They noted that haptic gloves allowed free-hand interaction without the need to hold a controller, enabling more direct and natural actions that closely aligned with real-life interactions. B5 and B9 stated that they would not have performed such actions with hand controllers and explicitly cited

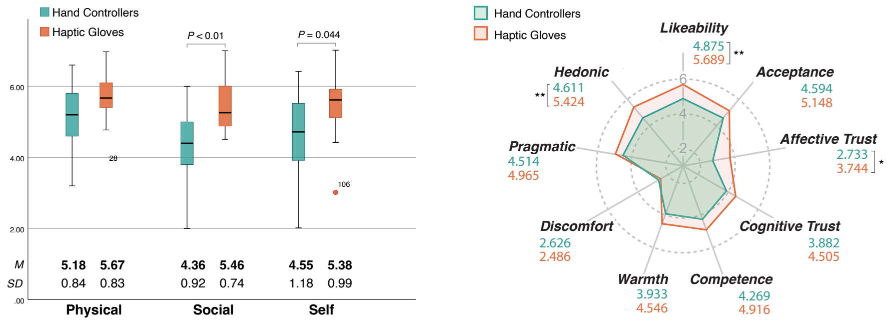

Fig. 8.2.: Quantitative Results. Left: Box plot of Multimodal Presence Scale (M: Mean, SD: Standard Deviations). Right: Participants' assessments of the robot based on estimated marginal means (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

this constraint, explaining that holding controllers restricted their ability to engage in these interactions: *'I don't think I would (high-five the robot) because I am not able to. With the controller, you have to hold it'* (B9). In contrast, B2 attributed their behaviour specifically to the increased tangibility of the robot in VR, made possible by the tactile and force feedback provided by the haptic gloves. This enhanced the robot's physical presence and led to the participant's greater emotional investment, ultimately prompting B2 to kick the robot when it failed to respond.

In addition, B2 and B4 expressed a heightened sense of full-body engagement due to the high level of immersion, with B2 describing it as *'my whole body got activated'*. In contrast, A8 and A11 from *Hand Controllers* group expressed an intention to use their feet to interact with the robot (e.g., to help it get unstuck) but did not act on it, citing uncertainty about whether such actions were *'allowed.'* Moreover, six participants from the *Hand Controllers* group reported difficulties with distance perception in VR, a challenge mentioned only once in the *Haptic Gloves* group. This limitation likely hindered participants in the *Hand Controllers* group from engaging in more embodied and exploratory behaviours.

8.6.2 Sense of presence

MPS: Descriptive analysis results indicated that participants in the *Haptic Gloves* group reported a higher sense of presence across all subscales compared to the *Hand Controllers* group (see Fig. 8.2). Independent samples t-tests showed no significant difference in physical presence ($t(34) = -1.662, p = 0.106$), but significantly higher scores for the *Haptic Gloves* in social presence ($t(34) = -3.601, p < 0.001$), and self presence ($t(34) = -2.094, p = 0.044$). The effect sizes (Cohen's $d = 0.86$ for social presence and $d = 1.13$ for self presence) indicate large effects, suggesting that the observed differences are practically meaningful despite the unequal sample sizes between groups.

Qualitative feedback: While all participants in *Haptic Gloves* group agreed that haptic feedback enhanced their sense of presence, eight noted that discrepancies with real-world haptic experience inevitably exist, such as the gloves' inability to simulate friction when touching objects and the insufficient force resistance when pushing the robot, failing to accurately reflect its real-world weight. Additionally, five participants noted that the device's substantial weight and its tethered nature of cable connection imposed limitations on their freedom of action. These limitations may have contributed to the absence of a significant difference in physical presence between groups.

Despite these limitations, four participants indicated that the natural interaction enabled by the haptic gloves led to a higher level of engagement in the virtual scene compared to their previous experiences in VR without haptic gloves. Some attributed this engagement to the greater actual physical effort required in the haptic glove setup (n=2). B2 additionally remarked that the experience felt more emotionally engaging due to the sensations being closer to real life. In contrast, A2 from *Hand Controllers* group likened pushing the robot by holding controllers to *'using a magical wand'*, suggesting lower engagement and seriousness compared to the haptic gloves experience.

The interviews also reflected how being able to physically feel the robot influenced participants' perceptions of the robot's presence. B4 noted that physically touching the robot made it *'more convincing that the robot truly existed,'* describing it as *'something real in front of me.'* Conversely, A2 and A5 from *Hand Controllers* group remarked that the lack of haptic feedback made the interaction feel like *'pushing the air,'* (A5) leading them to realise *'the robot is not real.'*

Four participants in *Haptic Gloves* group noted that the gloves gave them a sense of greater control over their body, with B12 stating, *'I have some power about using my hand or my body,'* and B11 describing *'my hand and my virtual hand become one.'* In contrast, three participants from *Hand Controllers* group reported feeling disconnected between their own body and the virtual one, stating *'the hands didn't really feel like my hands.'* (A18). These differences in experiencing embodiment could potentially be related to the higher self-presence scores observed in the *Haptic Gloves* group.

8.6.3 Participants assessments of the robot

Likeability: The *Haptic Gloves* group reported higher likeability scores than *Hand Controllers*, with a significant mean difference ($M_{diff} = 0.814, SE = 0.259, p = .004$, 95% CI [0.287, 1.341]) (Fig. 8.2, right). The effect size (Cohen's $d = 0.75$) suggests a moderate-to-large practical effect. The Group × Condition interaction effect was non-significant, $F(2, 68) = 0.537, p = .587$, indicating differences in likeability scores across conditions were consistent between groups.

Acceptance: The *Haptic Gloves* group reported higher mean acceptance towards the robot compared to the *Hand Controllers* group, but this difference was not significant ($M_{diff} = 0.554, SE = 0.291, p = .067$, 95% CI [$-0.036$, 1.144]). The Group × Condition interaction effect was also non-significant ($F(2, 68) = 0.416, p = .661$).

Trust: For affective trust, *Haptic Gloves* group reported higher scores than *Hand Controllers* group, with a significant mean difference ($M_{diff} = 1.011, SE = 0.485, p = .037$, 95% CI [$0.064$, 1.958]). The effect size (Cohen's $d = 0.67$) was moderate. For cognitive trust, the *Haptic Gloves* group also reported higher scores, but this difference was not significant ($M_{diff} = 0.623, SE = 0.375, p = .107$, 95% CI [$-0.139$, 1.385]). The Group × Condition interaction effect was non-significant for both affective ($F(2, 68) = 0.627, p = .537$) and cognitive trust ($F(2, 68) = 1.850, p = .165$), indicating that differences in trust scores across conditions were consistent between groups.

Robotic social attributes: Although *Haptic Gloves* group reported slightly higher competence ratings than *Hand Controllers* group, the difference was not significant, $M_{diff} = 0.647, SE = 0.309, p = .069$, 95% CI [$-0.024$, 1.317]. Similarly, warmth ratings were slightly higher in *Haptic Gloves* group, but this difference was not significant($M_{diff} = 0.613, SE = 0.378, p = .119$, 95% CI [$-0.154$, 1.380]). Discomfort ratings were comparable between the two groups, with no significant main effect of Group, ($M_{diff} = 0.140, SE = 0.257, p = .590$, 95% CI [$-0.380$, 0.660]). No significant Group × Condition interaction effects were found across all three subscales: Competence, $F(2, 68) = 0.592, p = .556$; Warmth, $F(2, 68) = 0.236, p = .790$; and Discomfort, $F(2, 68) = 0.238, p = .789$.

User experience: Pragmatic experience quality ratings were slightly higher in *Haptic Gloves* group compared to *Hand Controllers*, but this difference was not significant ($M_{diff} = 0.451, SE = 0.341, p = .195$, 95% CI [$-0.242$, 1.144]). However, hedonic experience quality was significantly higher in the *Haptic Gloves* group ($M_{diff} = 0.813, SE = 0.267, p = .004$, 95% CI [$0.275$, 1.351]), with a moderate-to-large effect size (Cohen's $d = 0.75$). No Group × Condition interaction effects were found for either subscale—pragmatic quality, $F(2, 68) = 0.227, p = .798$, or hedonic quality, $F(2, 68) = 0.120, p = .887$.

8.7 Discussion

8.7.1 Haptic simulation facilitates spontaneous bodily engagement

Our study results indicate that enabling haptic interaction in VR-based HRI study using haptic gloves significantly enhances participants' self-presence, defined as the feeling of connection to their virtual body, emotions, and identity (Lee et al., 2006). The more frequent and diverse natural bodily engagement observed among participants using haptic devices further highlights that heightened self-presence fosters more natural and a wider range of bodily interactions beyond task-focused behaviours. Spontaneous bodily engagement becomes increasingly critical in VR-based HRI studies as robots transition from static, controlled laboratory settings to everyday environments (Brown et al., 2024; Yu et al., 2024d), where interactions involve not only human collaborators who engage in predefined tasks but also casual bystanders. This shift renders human-robot interactions less predictable and more situated and emergent (Rosenthal-von der Pütten et al., 2020; Yu et al., 2024b), underscoring the need for VR-based HRI experiments to move beyond curated tasks towards capturing spontaneous interactions in dynamic, contextually diverse environments. In this context, simulating haptic sensations in VR plays a pivotal role in rendering a more realistic sense of embodiment that is necessary to effectively study these emergent human-robot interactions.

8.7.2 The relevance of haptic simulation for affective-related assessments

We did not find a significant interaction effect between Groups and Conditions in any assessment, indicating that the observed differences between robot help-seeking methods are consistent and not influenced by the type of VR interaction devices used. In contrast, Voit et al. (2019)'s study on comparing research methods to evaluate smart artefacts identified a significant interaction effect between the evaluation methods and the investigated artefacts, suggesting potential contradictions in artefacts comparison results when different evaluation methods are employed. The absence of an interaction effect in our study could be attributed to the fact that the inclusion of haptic sensations did not fundamentally alter the evaluation method, as the study remained within a VR setup. This validates VR, even without the inclusion of haptic sensations, as a robust tool for comparative studies in HRI experiments, ensuring that concept comparison results remain consistent regardless of whether haptic sensations are included.

However, main effects of Groups did exist for scales more closely related to affective perception, including likeability and affective trust. The ability to engage in direct physical interaction with the robot resulted in higher assessments of these affective dimensions (see Fig. 8.2, right). This could be attributed to two factors. First, our results indicate that participants using haptic gloves experienced enhanced social presence in VR, a sense of being together with another in virtual environments (Biocca et al., 2003). This aligns with prior work showing that haptic feedback can enhance social presence during interactions with human avatars in VR (Giannopoulos et al., 2008). Higher social presence fosters authentic and nuanced social interactions (Oh et al., 2018), potentially influencing their social perceptions of the robot. Second, it may also be explained by the fact that haptic sensation enables realistic physical contact through haptic gloves, which enhances the robot's perceived social presence, as direct touch fosters a stronger perception of the robot as a socially aware and engaging entity (Bainbridge et al., 2011; Lee et al., 2006). This type of physical realism has also been shown to intensify emotional engagement in social VR scenarios (Venkatesan et al., 2023), potentially leading participants to respond to robots in more emotionally authentic ways, which may further influence their affective assessments of the robot. Thus, when assessing human-robot social interactions in VR that involve direct physical contact, the absence of haptic feedback risks undermining the validity of affective-related evaluations.

8.7.3 Limitations

Our study serves as an initial exploration of introducing highly realistic haptic simulation into VR-based HRI studies, which is based on a relatively small sample size with unequal group distributions. Despite careful statistical treatment, this limitation may impact the generalisability of our findings. Second, while our comparison focused on two setups—haptic gloves and hand controllers—the impact of haptic sensation cannot be entirely isolated from other device-related differences, such as equipment weight and varying degrees of hand movement freedom, the latter of which could enhance presence and natural engagement in VR (Krogmeier et al., 2023; Bailenson et al., 2003). Future studies should consider additional control conditions to better disentangle these factors. Finally, while our findings provide valuable insights, the study was conducted within a specific robot help-seeking scenario in urban public spaces. Future research is needed to extend these investigations to a broader range of HRI contexts, incorporating diverse scenarios and interaction instances.

8.8 Conclusion

Through a comparison of a VR-based human-robot interaction using hand controllers and haptic gloves, we found that enabling haptic sensation resulted in enhanced social and self-presence. Participants also demonstrated more diverse and natural bodily engagement with the robot when haptic sensation, including both tactile and force feedback, was provided. Furthermore, haptic sensation significantly influenced participants' affective-related perceptions of the robot. These findings underscore the importance of incorporating haptic sensations into VR-based HRI studies, particularly for investigating spontaneous reactions to robots and assessing social interactions involving direct physical contact.

9 Peek into the ‘White-Box’: A Field Study on Bystander Engagement with Urban Robot Uncertainty

9.1 Preamble

Xinyan Yu, Marius Hoggenmueller, Martin Tomitsch (2025). Peek into the ‘White-Box’: A Field Study on Bystander Engagement with Urban Robot Uncertainty. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI ’25)*

This chapter investigates causal collaboration in situations involving bystanders in resolving urban robots’ uncertainties, as identified in Chapter 3. The speculative *peephole* concept developed in this chapter builds on the design investigation in Chapter 6, and extends the playful help-seeking strategy from Chapter 7 by rendering playfulness in a more implicit and subtle manner. We implemented the *peephole* concept on a mobile robot and conducted a Wizard-of-Oz field study to investigate passersby’s spontaneous reactions to the design. The design process and concept in this study continue to address RQ2: *“How can we design interactions that facilitate casual collaboration between bystanders and urban robots?”* Furthermore, passersby’s spontaneous reactions to the robot and the analysis of interviews with bystanders yield insights into how engagement with urban robots’ uncertainty shapes their perceptions and attitudes toward the robots, thereby also addressing RQ3: *“How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?”*

This chapter was originally published as a paper at the CHI Conference on Human Factors in Computing Systems (CHI) and is available in the ACM proceedings of this conference. The formatting and referencing style in this chapter have been adapted from the original journal article to fit the thesis’ standards.

9.2 Abstract

Uncertainty inherently exists in the autonomous decision-making process of robots. Involving humans in resolving this uncertainty not only helps robots mitigate it but is also crucial for improving human-robot interactions. However, in public urban spaces filled with unpredictability, robots often face heightened uncertainty without direct human collaborators. This study investigates how robots can engage bystanders for assistance in public spaces when encountering uncertainty and examines how these interactions impact bystanders' perceptions and attitudes towards robots. We designed and tested a speculative 'peephole' concept that engages bystanders in resolving urban robot uncertainty. Our design is guided by considerations of non-intrusiveness and eliciting initiative in an implicit manner, considering bystanders' unique role as non-obligated participants in relation to urban robots. Drawing from field study findings, we highlight the potential of involving bystanders to mitigate urban robots' technological imperfections to both address operational challenges and foster public acceptance of urban robots. Furthermore, we offer design implications to encourage bystanders' involvement in mitigating the imperfections.

9.3 Introduction

Robot's autonomous decision-making relies on the acquisition and analysis of environmental data, a process inherently subject to uncertainty from various sources, such as sensor noise and inaccuracies in machine learning models (Loquercio et al., 2020). Integrating human perception and cognition into robot decision-making can effectively address such uncertainty, and is also essential for facilitating smoother human-robot interactions and fostering trust (Leusmann et al., 2023; Schömbs et al., 2024).

The uncertainty challenges become more pronounced when robots transition from relatively static and controlled environments to public urban spaces. These contexts are characterised by increased levels of dynamics and unpredictability (Rosenthal-von der Pütten et al., 2020; Yu et al., 2024d; Weinberg et al., 2023), and urban robots often operate unsupervised, lacking human collaborators to turn to when uncertainty arises. This absence of support can lead to undesired decision-making, resulting in negative outcomes that not only hinder operational effectiveness but also undermine public perception of these technologies. A notable example occurred in September 2022, when a delivery robot, after a moment of hesitation, decided to cross into a crime scene, blatantly ignoring police tape and leaving onlookers confused and surprised. The incident was captured on video[1] and quickly went viral on social media, sparking public concerns about the reliability of the technology.

As robots become increasingly prevalent in public urban spaces, bystanders—defined as *'incidentally copresent persons'* (InCoPs) (Rosenthal-von der Pütten et al., 2020), individuals who do not have any prior intentions to engage with the robot—are gaining attention in human-robot interactions. Casual collaboration between bystanders and robots can emerge, particularly in situations where the robot requires assistance (Yu et al., 2024b; Chi et al., 2024; Holm et al., 2022; Pelikan et al., 2024; Weinberg et al., 2023). These emerging participants in HRI have the potential to assist urban robots in resolving uncertainty. Therefore, it is crucial to investigate how to engage bystanders in addressing such robot uncertainty, as well as how these interactions shape bystanders' perceptions and attitudes towards robots.

Distinct from traditional human-robot collaboration settings, the engagement of bystanders in casual collaborations requires tailored interaction strategies. Unlike traditional collaborators, who have a pre-established collaborative relationship and shared task goals, bystanders have no obligation to engage with the robot. Thus, engaging bystanders should consider minimising intrusiveness while fostering their self-initiative, rather than creating a sense of obligation, which can often result from explicit, direct verbal prompts (Babel et al., 2022c; Yu et al., 2024a). To address this, we developed a speculative *peephole* design concept that draws on the considerations of non-intrusiveness and implicit initiative-eliciting. Inspired by the principles of ludic engagement—*'activities motivated by curiosity, exploration, and reflection rather than externally defined tasks'* (Gaver et al., 2004)—this concept conceals the robot's uncertainty information behind a pair of binocular scopes, which open only when uncertainty arises. Rather than exposing and broadcasting robot uncertainty information through explicit modes of communication (e.g., visual displays or spoken language), the intent of the concept is to intuitively elicit bystanders' curiosity and encourage them to peek at hidden information. The peephole transforms direct help requests into a self-initiated, playful discovery process while reducing the persuasiveness and minimising the disruption that direct help requests could cause.

We built a mobile robot resembling a typical sidewalk service robot (e.g., delivery robot) to implement this concept and probed it in a Wizard of Oz field study (Dahlbäck et al., 1993), in order to investigate bystanders' spontaneous reactions to the non-intrusive and initiative-eliciting engagement strategy. The robot

[1] Available at `https://www.vice.com/en/article/93adae/food-delivery-robot-casually-drives-under-police-tape-through-active-crime-scene`.

was deliberately staged to get stuck in scenarios where it faced uncertainty, i.e., encountering ambiguous obstacles in its path. The field study was conducted across three different locations over a period of nine days in total, where we observed bystander reactions and conducted interviews. The design artefact evolved throughout the study, informed by on-site observations and reflections. Our work aims to investigate how bystanders respond when robots engage them in situations of uncertainty and examine the impact of such engagement on people's perceptions and attitudes towards robots. Additionally, we seek to uncover the multifaceted nature of employing implicit and non-intrusive strategies to engage bystanders in public spaces.

Our work contributes to the fields of HCI and interaction design by: (1) developing a speculative design concept that engages bystanders in resolving urban robots' uncertainties and documenting the artefact's evolution through a field study; (2) providing empirical insights into the potential of involving bystanders to mitigate urban robots' imperfections, not only addressing urban robots' operational challenges but also fostering their public acceptance; (3) offering design implications for implicit and non-intrusive engagement strategies that encourage casual human-robot collaboration. Our investigation aligns with emerging design research perspectives (Lupetti et al., 2019; Kuijer and Giaccardi, 2018; Marenko and Van Allen, 2016), which increasingly view human-robot interaction as a symbiotic relationship rather than focusing solely on robots' independent capabilities.

9.4 Related Work

9.4.1 Integrating human autonomy in AI

As AI systems become increasingly sophisticated and prevalent, concerns about their accuracy, fairness, and ethical implications have grown. Maintaining human autonomy in the loop of AI decision-making has emerged as a crucial strategy to address these issues (Zanzotto, 2019; Wu et al., 2022; Shneiderman, 2022). In this paradigm, humans have the opportunity to evaluate (e.g., loan decisions or crime judgements made by AI (Nakao et al., 2022; Agudo et al., 2024)), modify (e.g., robot vision recognition results (Cai and Mostofi, 2021; Abraham et al., 2021)), and contest (e.g., decisions made by public AI systems (**Alfrink2023**)) the results produced by AI systems, particularly when the system has uncertainty in its decisions (Abraham et al., 2021; Malinin and Gales, 2018; Corbière et al., 2019). For example, (Abraham et al., 2021) proposed a vision-based robotic system with adaptive autonomy, which temporarily lowers its autonomy level to involve human operators in decision-making when the reliability of its computer vision model is compromised. In addition to enhancing AI decision-making results, a growing body of research is advocating for interactive machine learning, which actively engages humans in the learning processes of machine learning models (Fails and Olsen Jr, 2003), further centering human autonomy in the development of AI systems.

While the involvement of humans in AI has traditionally focused on experts with professional knowledge, researchers have increasingly emphasised the inclusion of non-experts (Ramos et al., 2020). The HCI community has also begun to respond to this emerging paradigm by exploring the development of interaction strategies that enable non-experts to actively participate in the AI decision-making and development process (Yang et al., 2018; Feng and Mcdonald, 2023; Nakao et al., 2022).

9.4.2 Robot uncertainty and human intervention

Robot's autonomous decision-making relies on the acquisition and analysis of environmental data, during which inherent uncertainties can arise from various sources, such as sensor noise and inaccuracies in machine learning models (Loquercio et al., 2020). In human-robot collaborative tasks, it is essential for robots to communicate uncertainties to their human collaborators, enabling humans to better understand the robots' operations and address these uncertainties in their responses, thereby fostering optimised collaboration and enhancing trust (Schömbs et al., 2024; Leusmann et al., 2023; Hough and Schlangen, 2017). Additionally, informing humans of uncertainties allows robots to benefit from human-provided information that helps to reduce these uncertainties (Shin et al., 2023; Abraham et al., 2021; Schömbs et al., 2024). To communicate uncertainty to human collaborators, previous research has explored the use of verbal (Shin et al., 2023) and non-verbal cues, such as motion speed (Hough and Schlangen, 2017), hesitation gestures (Moon et al., 2021), and graphic visualisation (Schömbs et al., 2024).

Shifting from relatively static and controlled human-robot collaborative settings (e.g., labs, factories), robots are now operating in public urban spaces characterised by increasing uncertainty due to their unpredictable and ever-changing nature (Alatise and Hancke, 2020; Ferrer et al., 2013b). However, urban robots often operate unsupervised, without human collaborators to rely on when uncertainty arises. In such instances, bystanders could serve as a source of assistance, yet urban robots' uncertainty always remains hidden, preventing bystanders from engaging in addressing these challenges. While there is no research directly investigating the engagement of bystanders in addressing robot uncertainty in public spaces, several notable precedents exploring bystander input to supplement robotic autonomy highlight its potential. For instance, a speculative project involving a wandering robot, Tweenbot, devoid of sensors and autonomous navigation, successfully relied on the assistance of passersby to reach its destination (Kinzer, 2009). Similarly, the Autonomous City Explorer (ACE) navigated urban spaces by soliciting directions from pedestrians, foregoing the use of maps or GPS systems (Weiss et al., 2010).

9.4.3 Casual human-robot collaboration

With robots transitioning from controlled to uncontrolled environments, casual collaborations—distinguished from the planned and anticipated human-robot collaborations between robots and human teammates (Cila, 2022)—are increasingly happening spontaneously between robots and bystanders in public spaces. Recent field observation studies have witnessed such casual collaboration in various situations where urban robots are in need of assistance. For example, pedestrians have voluntarily assisted immobilised robots by removing obstacles (Weinberg et al., 2023), giving delivery robots struggling in heavy snowfall a gentle push (Dobrosovestnova et al., 2022), or even pausing their ongoing work to allow delivery robots to pass through (Pelikan et al., 2024).

In contrast to traditional human-robot collaboration, the dynamics of casual collaboration shift significantly due to misaligned task objectives and their role as non-obligated participants in relation to urban robots. Additionally, contextual factors such as task scenarios and the bystander's current activity (Kerstin et al., 2014; Hüttenrauch and Eklundh, 2006), the robot's perceived legitimacy and risk (Booth et al., 2017b), along with subjective factors like trust and perceived robot competence (Cameron et al., 2015), collectively influence the formation of such casual collaboration. Furthermore, Dobrosovestnova and Reinboth (2023) brought forth a nuanced discussion on the complexities of bystanders assisting commercially deployed robots in public spaces. They use the notion of ambiguity as a productive lens to shed light on different perspectives in robot-helping situations, highlighting concerns around invisible labour but also acknowledging the relational and affective dimensions of these interactions.

Thus, there is a need for tailored design strategies to effectively engage bystanders in casual collaboration with robots. However, both academic research (Kerstin et al., 2014; Liang et al., 2023; Rosenthal et al., 2012; Wullschleger and Brega, 2002) and commercially deployed robots (Boos et al., 2022) predominantly rely on verbal communication to facilitate these interactions, with limited exploration of using other less intrusive approaches that suited to the bystander's non-obligated nature (Holm et al., 2022). Recognising this gap, Yu et al. (2024b) explored the use of non-verbal strategies to foster casual human-robot collaboration and highlighted the potential of leveraging the inherent expressiveness in the functional aspects or form of robots. They emphasise the need for implicit, non-persuasive approaches that frame bystander assistance as a voluntary, spontaneous act rather than an obligation. Their subsequent study explored game-inspired concepts as robot help-seeking strategies (Yu et al., 2024a). They found that robot help-seeking through verbal speech was perceived as impolite by bystanders, underscoring the potential of curating humans' innate playfulness as an intrinsic motivation to foster casual collaboration, rather than relying on explicit help requests. While providing insights into engaging bystanders in an implicit manner, these findings were derived from controlled lab settings, where spontaneous reactions from bystanders could not be observed in a fully natural context.

9.5 Field Study

Involving human autonomy can enhance AI decision-making, particularly in scenarios where system confidence is low, as exemplified by robots facing uncertainty. While prior research has explored engaging human collaborators in mitigating robot uncertainty—demonstrating benefits such as optimised operation and enhanced trust—the dynamics of engagement between bystanders and urban robots remain unexplored. Drawing on insights from previous work on strategies for casual human-robot collaboration, we developed a speculative design concept and probed it in a field study to investigate bystanders' reactions in real-world settings and assess how such engagement shapes public perceptions and attitudes towards robots.

9.5.1 Design concept

Design rationales

Informed by both theoretical underpinnings and practical design research investigations on robot help-seeking from bystanders (detailed in Section 2), our design was initially guided by two key considerations: (1) the initiative should come from the bystanders themselves, without being prompted by explicit verbal requests that could create a sense of obligation, and (2) the design should minimise disruption to the surrounding environment and the activities bystanders are currently engaged in.

To this end, our design draws inspiration from ludic engagement (Gaver et al., 2004), which emphasises activities motivated by curiosity, exploration, and reflection rather than externally-defined tasks. This approach-initially introduced in HCI and interaction design research-has since been extended to the domain of HRI (Lee and Jung, 2020; Lee et al., 2020; Hoggenmueller et al., 2020b). For example, Lee et al. (2020) presented a case study where humans' inherent playfulness was leveraged by a bubble-bursting robot to captivate people in public space and create enjoyable experiences. The ability of ludic engagement to spark curiosity and promote interactions among passersby aligns with our goal of encouraging bystander-initiated involvement and has the potential to foster positive and enjoyable experiences. Additionally, the exploratory nature of ludic engagement and its openness addresses the ambiguities of robot help-seeking from bystanders (Dobrosovestnova and Reinboth, 2023), allowing bystander reactions to be curated in an unstructured and spontaneous manner.

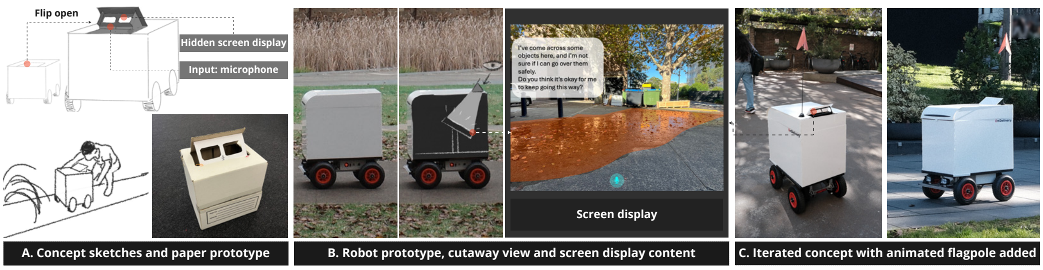

Fig. 9.1.: Concept development from initial sketches to final implementation: (A) Concept sketches, interaction illustrations, and a paper prototype in the early stage; (B) Robot prototype during the initial deployment, with a cutaway view and screen display content; (C) The iterated design concept featuring an added animated flagpole.

The peephole concept

The universal metaphor of an AI system as a 'black-box,' indicating its opaque internal processes, serves as the starting point for our design. Our goal is to allow bystanders to access the information concealed within this 'black-box' when robot uncertainty occurs. This concept aligns well with the interactive strategy of *peephole* to create engaging interactions, as proposed in (Dalsgaard and Dindler, 2009). This strategy leverages the tension between hidden and revealed information to foster engagement, a technique successfully used in museums to encourage visitors to explore cultural and natural history exhibits (Cassinelli and Ishikawa, 2005; Edmonds et al., 2006). The curiosity-driven nature of *peephole* interactions embodies the exploratory and unstructured essence of ludic design, aligning well with our aim to create engagement that elicits initiative from bystanders while minimising intrusiveness.

Our concept involves a pair of binocular-like lenses that flip open when the robot encounters uncertainties (see Fig.9.1, A). Information about the uncertainty and a request for assistance are displayed on screens hidden behind these lenses. This setup leverages the human instinct of curiosity—'peeking'—to motivate bystander engagement. Bystanders need to bend over to view the information, which is designed to bring them to the same level and perspective as the robot. This approach fluently allows bystanders to assess the environment from the robot's point of view, making it easier for them to understand the situation and offer help.

The displayed content includes a colour overlay on the objects that the robot is uncertain about recognising and making decisions on (e.g., a puddle of water with leaves that cast reflective light, which can be challenging for computer vision to interpret). The image with the colour overlay is accompanied by a textual description of the situation and a request for help (see Fig.9.1, B). Our uncertainty visualisation is similar to the visualisation approach in (Colley et al., 2021), where the internal processes of autonomous vehicles were communicated to passengers through the semantic segmentation visualisation by highlighting recognised objects.

In terms of input, we opted for an unstructured approach by allowing bystanders to respond freely via speech, using a microphone to capture their input. The decision to use speech as the input rather than selecting different options (e.g., via buttons) was made to encourage more open-ended responses.

Concept evolving during deployment

As the field study progressed, we noticed a low percentage of involvement during the initial days of deployment, with the majority of passersby walking past the robot without paying much attention to it. Thus, as part of our iterative design process, we decided to add additional elements that can attract bystanders' attention to increase engagement. This ongoing development of the design concept aligns with the Research through Design (RtD) approach (Zimmerman et al., 2007) that we followed, which emphasises the iterative, exploratory process where insights continuously emerge and shape the research.

Prior research has highlighted the human tendency to perceive non-verbal gestures from non-humanoid robotic objects as social signals (Novikova and Watts, 2014; Erel et al., 2022; Erel et al., 2024; Press and Erel, 2022), sometimes inviting further interactions Ju and Takayama, 2009; Sirkin et al., 2015b. Social meanings can be attributed to a robot's gestures, even when they are minimal and abstract. For instance, the *Greeting Machine*, an abstract non-humanoid robot, was designed to signal positive and negative social cues during open encounters. In this concept, a small ball moving forward on a dome was perceived as a willingness to interact, while backward movement signalled reluctance (Anderson-Bashan et al., 2018). Drawing inspiration from such effective use of gestural cues to engage interaction in an abstract and minimal manner, and to maintain consistency with the typical design of commercial delivery robots, we added an animated flagpole, a component commonly seen on such robots. The flagpole's animation was designed to wave to attract attention, rotate to indicate a search for help, and repeatedly point in a specific direction, mimicking nodding to directly address an individual.

After another period of deployment without achieving a significant increase in engagement, we further tested whether adding auditory cues could more effectively capture attention from passersby. We introduced a two-note beep, beginning with a higher pitch and followed by a lower one. This sound was chosen because it is interpreted as 'negative' in musical terms, potentially signalling something that requires attention, a strategy often used to raise alerts among people (Foley et al., 2020) and has been used in robot help-seeking (Holm et al., 2022).

Implementation

We build a mobile robot to implement the concept. The robot's shell is constructed from white acrylic with a curved 3D-printed front, resembling a typical delivery robot (see Fig. 9.1, C). Its dimensions, approximately 40 cm wide, 60 cm long, and 60 cm high, are comparable to those of a standard sidewalk delivery robot. To ensure passersby identified it as a delivery robot rather than a research prototype, we added an 'on delivery' sign to the robot. The robot is powered by a four-wheeled robotic base that can be remotely controlled via a gamepad. The flip-open lenses are operated by a stepper motor, which is controlled by an Arduino board equipped with a Wi-Fi module for remote control. The flagpole is animated by a set of two-dimensional servos, allowing 2-degree of freedom rotation across two different axes, which is also remotely controlled via a gamepad. Finally, the auditory cue is played through a Bluetooth speaker placed inside the robot.

9.5.2 Wizard of Oz set-up

The field study followed the Wizard of Oz method (Dahlbäck et al., 1993), wherein two researchers acted as wizards to control the robot's movement, open the lenses, and animate the flag (an overview of the Wizard of Oz setup is shown in Fig. 9.2). Wizard 1 remotely drove the robot from the starting point to the location where it encountered uncertainty. Once bystanders intervened and helped resolve the issue, Wizard 1 restored the robot's movement. After each instance of successful engagement and the subsequent interview, Wizard 1 drove the robot back to the starting point and paused for a while before returning to the interaction location where uncertainty was staged. This was intended to ensure that the following passersby had not witnessed the previous interaction and interview. Wizard 1 also controlled the animated flagpole and peephole using a gamepad. Wizard 1 was given instructions on pre-defined motions, including rotating to search for help, waving to attract attention, and nodding to address passersby. In addition, Wizard 1 had the flexibility to adjust or expand these motions in response to bystander interactions.

Wizard 2 monitored what bystanders said in response to the robot via a Zoom call between a laptop and the iPad inside the robot. In response to what passersby said to the robot, Wizard 2 remote-controlled the screen inside by manipulating the displayed text with several pre-determined phrases. For example, phrases like *'Sorry, I don't understand. Can you repeat?'* were used to elicit clearer instructions when bystanders' utterances were unclear, while *'Thank you'* was displayed in response to bystanders' assistance. This was achieved by manipulating slides over the shared Zoom screen, simulating a conversational interface.

9.5.3 Wizard of Oz set-up

9.5.4 Location and deployment duration

The field study was conducted in three locations across our university campus, including (1) a sidewalk in front of a faculty building situated at the corner of the university campus, (2) a main pedestrian path that connects public transportation to several major university facilities, and (3) a courtyard inside a faculty building that leads to the main street outside of campus. The first two locations shared similar characteristics, with passersby primarily in commute mode, while in the third location, people were more likely to dwell and engage in social activities. We

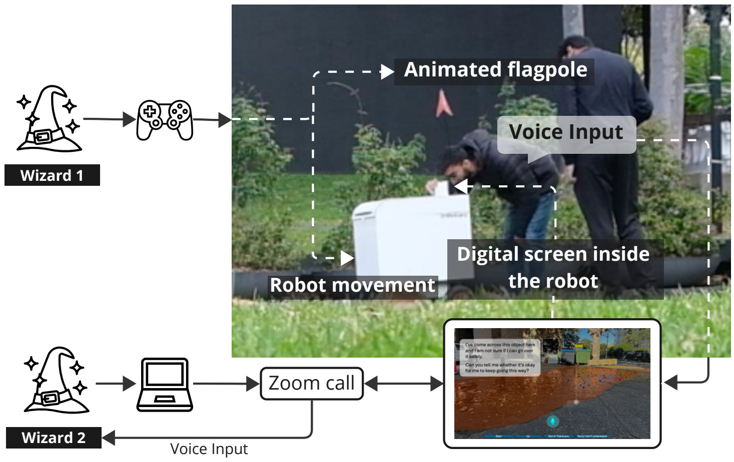

Fig. 9.2.: Wizard of Oz set-up overview

staged uncertainty by placing a puddle of water with leaves in the robot's path, where the reflective light could confuse the computer vision system and complicate decision-making, even though it was safe to proceed.

The robot was trialled for approximately 6.5 hours over five weekdays at the first location, 5.5 hours over three weekdays at the second location, and 3.5 hours over three weekdays at the third location, totalling 15.5 hours of deployment (see Table 9.1). All sessions took place during the semester, ensuring that the flow of people at each location remained roughly consistent across the deployment days.

9.5.5 Data collection

A camera was set up approximately 5 meters from the robot's interaction location to video record individuals passing by or interacting with the robot. Additionally, researchers recorded observational notes on-site using audio to complement the video recordings. Conversations that passersby had with the robot were also audio recorded via the Zoom call that was set up to control the screen inside the robot. During the deployment, three researchers were on-site: two operated as wizards controlling the robots, while the third researcher provided support in observation, note-taking, and conducting interviews.

During the 15.5 hours of field study, we observed twenty-night instances where passersby (p1–p29) intervened to help the robot resolve its uncertainties. Twelve of

Tab. 9.1.: Overview of Study Locations and Number of Engagements

Study Location	Description	Duration	Engagement Count
	**Location 1**: A sidewalk in front of a faculty building situated at the corner of the university campus **Average Foot Traffic***: 7.3/min	**3.5hrs** (Iteration 1) **3hrs** (Iteration 2)	**8** (Iteration 1) **6** (Iteration 2)
	**Location 2**: A main pedestrian path that connects public transportation to several major university facilities **Average Foot Traffic***: 28.2/min	**2.5hrs** (Iteration 2) **3hrs** (Iteration 3)	**4** (Iteration 2) **6** (Iteration 3)
	**Location 3**: A courtyard inside a faculty building that leads to the main street outside of campus **Average Foot Traffic***: 5/min	**3.5hrs** (Iteration 2)	**5** (Iteration 2)

* Average foot traffic is estimated by manually counting people passing by in the video over several periods, totaling 15 minutes for each location.
** Iteration 1: the initial peephole concept; Iteration 2: peephole concept with animated flagpole added; Iteration 3: peephole concept with both animated flagpole and auditory cue added.

these interactions[2] involved individual participants, while the remaining 17 were group engagements. The rate of passerby involvement was relatively low given the average foot traffic and study duration at the three locations: 7.3 people/min over 6.5 hours at Location 1, 28.2 people/min over 5.5 hours at Location 2, and 5 people/min over 3.5 hours at Location 3 (see detailed distribution in Table 9.1).

We approached and interviewed passersby who engaged with the robot, such as those who looked through the peephole or assisted the robot. Additionally, we interviewed passersby who drew their attention to the robot, for example, by pausing or gazing at it but eventually left without further interaction. The interviews included questions about participants' interactions with the robot and their opinions on intervening in the robot's operation as bystanders when the robot encounters uncertainties. Due to the nature of street interviews, some individuals hurriedly cut off or declined the interview request (n=5). As a result, we had to keep the interviews short and concise, ranging from 3 to 7 minutes (similar to comparable studies investigating interactions with robots in public spaces (Hoggenmueller et al., 2020b; Hoggenmueller et al., 2020a; Lee et al., 2020)). In total, we conducted 24 interviews with bystanders who engaged in interaction with the robot (p1-p11, p13-p22, p24-p25, p27) and 21 interviews with those who left without further interaction (c1-c21).

[2] An interaction was defined as any distinct occurrence where one or more passersby engaged with the robot to assist it in resolving a situation

The study followed a protocol approved by our university's human research ethics committee, and also complied with local regulations concerning data collection and the incidental recording of individuals in public spaces. We approached participants after their interactions with the robot to obtain their verbal consent for participation in interviews. Due to the rapid nature of street interviews, participants were not provided with an introduction to the Wizard of Oz method but received a printed participant information statement with further details on the study. In line with similar practices for field research in public spaces (Brown et al., 2024), we did not seek consent from passersby who were incidentally included in the video recordings; however, measures were taken to protect their privacy by blurring identifiable features.

9.5.6 Data analysis

The data analysis employed a cross-analysis approach, where interview data provided deeper insights and explanations for passersby's behaviours observed during the field study, while video recordings enriched the contextual understanding and supported the comments made during the interviews. The first author closely examined the video recordings, documenting the incidents where passersby either helped the robot or noticed it without further interaction. These observations were captured through textual descriptions and supplemented by screenshots from the video. Subsequently, an approximately one-hour meeting was held between the three authors to discuss and review the interaction patterns identified by the first author during the analysis process.

To analyse the interview data, we transcribed the interview recordings and conducted a thematic analysis (Braun and Clarke, 2006; Braun and Clarke, 2019). The first author examined and coded the data following an inductive approach, deriving sub-themes by identifying recurring patterns. This initial coding scheme was then discussed and refined during another one-hour meeting among three authors. Subsequently, the sub-themes derived from these codes were deductively grouped into final themes, structured around the two main aspects of our investigation: (1) supplementing interaction patterns identified from video analysis to interpret the reasons that influenced bystanders' behaviours and (2) understanding the impacts of engagement in the robot's uncertainty on bystanders' perceptions and attitudes toward the robot. This mixed approach aligns with Braun and Clarke (2019)'s reflexive thematic analysis, where they point out that coding could involve a blend of inductive and deductive processes rather than adhering strictly to one or the other.

9.6 Results

In this section, we first report common patterns of passersby's reactions, illustrated through representative instances derived from video analysis. We then supplemented our observations with interview data to interpret the triggers and barriers that influenced bystanders' involvement. Finally, we examine how bystanders' engagement during the robot's uncertainty impacts their perceptions and attitudes towards the robot, focusing on three key aspects: (1) maintaining human autonomy, (2) building connection through vulnerability and reciprocity, and (3) enhancing trust.

9.6.1 Passive observation without engagement

Low level of attention

For much of the deployment, the majority of passersby walked past the robot without noticing it at all. Due to the commuter-focused nature of study locations 1 and 3, most people were singularly focused on reaching their destination, moving with purpose and not taking the time to look around. The robot did not receive a significantly higher level of attention after the animated flag pole was added. However, it managed to draw more attention after an audio cue was introduced, as we observed an increase in the number of passersby glancing at the robot due to the sound. This was further evidenced by instances where individuals who were originally focused on their phones shifted their attention to the robot after hearing the audio cue. Despite this increase in attention, the sound cue did not result in a significant increase in further engagement with the robot.

Remaining indifferent

Among those who did notice the robot, a common interaction pattern was varying levels of attention—from brief stares to pausing for a longer observation—before eventually leaving without further engagement. Most passersby who noticed the robot would stare at it while continuing on their way, turning their heads to keep it in sight without slowing down, indicating an interest in observing the robot without a commitment to further engagement (see Fig.9.3, top). Some passersby paused to observe the robot from a distance. For example, as shown in Fig.9.3, middle, one passerby did not stop initially but paused after passing the robot to observe it. This individual repeated this pattern of walking a bit further, then pausing to observe again, several times before eventually leaving without further interaction. A smaller portion of passersby exhibited stronger interests in the robot by approaching the robot more closely, taking photos, or discussing it with companions, though they too eventually left without further engagement. As shown in Fig.9.3, bottom, one passerby initially walked past the robot, then paused, turned back, and circled it for closer inspection. They then took a photograph of the robot before leaving.

Looking around and searching

Another noticeable observation was that some passersby would look around, seemingly searching for something after spotting the robot, which often led to their eventual departure without further interaction. In Fig.9.3, one passerby can be seen turning their head repeatedly, scanning the surroundings, even as their companion began interacting with the robot. In the interview, this participant explained that they believed the robot was being tested and were looking for the person in charge of it. This observation was particularly pronounced during the first few days of the field study at Location 1, where foot traffic was relatively low, even leading to instances where the Wizards were spotted during the pilot run.

Fig. 9.3.: Varying levels of attention displayed by passersby while remaining indifferent.

9.6.2 Getting involved and offer help

Among the 29 interaction instances where passersby intervened to help the robot resolve its situation, 27 involved looking into the peephole, reading the information about the robot's uncertainty, and offering help accordingly. In two instances, the participants did not look into the peephole; instead, they inferred the situation from the context and helped the robot by clearing the path. Fig.9.4 illustrates a typical interaction sequence of how a passerby becomes involved in helping the robot navigate an uncertain situation.

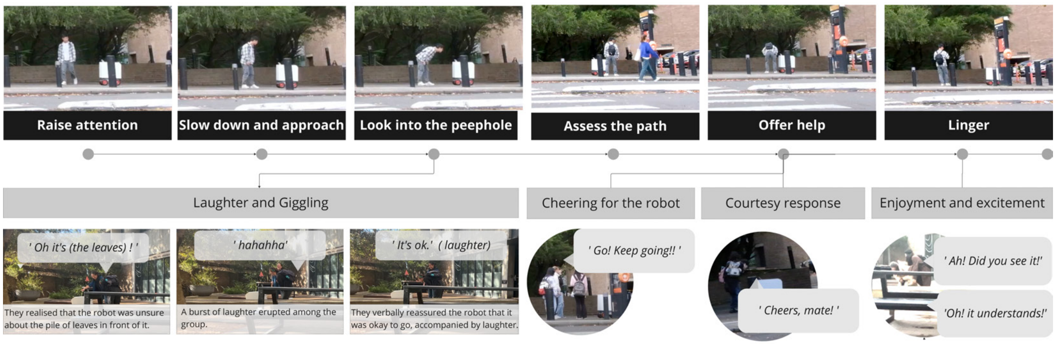

Fig. 9.4.: Interaction sequence of a passerby getting involved and resolving the robot's uncertainty, with additional observations supported by supplementary images and quotations.

Reactions to uncertainty: laughter and giggling

After noticing the robot, passersby slowed down, approached it, and bent down to look through the peephole. Upon seeing the screen and reading about the robot's uncertainty information, a common reaction among people in groups was laughter and giggling, sometimes sparking discussions within groups, describing the robot as *'So Cute!'*. As shown in Fig.9.4, bottom, the group erupted in laughter when they realised the robot was unsure about the pile of leaves and puddle in front of it. They later responded to the robot, saying *'it's okay,'* while their laughter continued. This sense of enjoyment and delight, particularly when discovering the robot's limitations, was articulated by p18 as being *'pleasantly surprised'*. They further described the experience as akin to *'finding a gem outside, you didn't expect it'*.

Offering help

Upon understanding the robot's uncertainty, participants commonly exhibited a behaviour of briefly examining the obstacle and assessing the path ahead before offering any response. To respond to the robot, the majority (n=23) verbally communicated with it, often saying things like *'Yeah, just keep going'* or *'Yes, it's safe to go'* to indicate it was safe to proceed. The utterances were generally short and precise. We also observed groups cheering for the robot, saying things like *'Go! Keep*

Going!' in an encouraging tone. Additionally, three participants demonstrated social etiquette by responding to the robot's *'Thank you!'*—displayed on the screen by the wizard—with phrases like *'Cheers, mate!'* (p1) or *'You're welcome.'* (p21)

Other than verbal response, four people attempted to resolve the robot's uncertainty by physically clearing the path ahead. For example, after checking the screen, p19 walked around to the front of the robot, cleared the path, and then returned to the peephole, saying to the robot *'Yeah, there are no more leaves'*. Two participants directly pushed the robot forward after assessing that the path ahead was safe.

Enjoyment and excitement after interaction

After giving the robot instructions, people tended to linger, eagerly anticipating how the robot would respond to their input. When the robot resumed its movement (initiated by the wizard), it often sparked genuine surprise and excitement, especially in groups where people's reactions were more animated. People would exclaim *'Wow!'*, laugh, or turn to their friends with joyful astonishment, saying things like *'Did you see that?!'* or *'Oh, it understands!'* as they marvelled at the robot's responsiveness (see Fig.9.4, bottom-right).

The observed enjoyment and excitement were supported by subsequent interviews, where the majority of participants reported positive experiences when engaging with the robot during its moments of uncertainty (n=13). Some participants described the experience as *'fun'* (p15) or *'interesting'* (p8). However, one participant expressed a negative view, stating *'I don't like that'*, as they believed that *'[. . .] robots, you know, by definition, should be very binary—right on or off,'* rather than displaying uncertainties and requiring human assistance.

9.6.3 Engagement barriers and triggers

Barriers to engagement

The level of indifference and low engagement was unexpected, as at the time of the study, no mobile robots were deployed on the university campus or in the broader region where the campus is located. Given this novelty, we anticipated that the robot would spark greater interest and a higher level of involvement from passersby.

To understand the reasons for this, we interviewed 21 passersby who noticed the robot (identified by observing their gaze towards it) but eventually moved on. Nine passersby indicated that they were unaware of the robot's need for assistance and continued on their way due to the robot's implicit signalling of its need for help. Two of them misinterpreted the robot's flagpole waving as a mere *'greeting'* rather than a request for help. Additionally, three passersby described the beep sound as simply drawing attention, viewing it as a *'warning to avoid bumping into it'* rather than an indication that the robot required assistance. Three participants indicated that they were in a rush and didn't pay much attention to the robot.

The remaining 9 passersby, despite understanding the robot was in a difficult situation, remained indifferent. They inferred from the flag motion, beep sound, and the robot's lack of movement that it might be stuck, yet chose not to engage. Five of these individuals mentioned that their indifference stemmed from the belief that the robot was someone else's property, and therefore, they felt they were not meant to interact with it. For example, c13 suggested that they *'thought it would just be rude to touch it'*. Two of them further expressed concerns about *'break[ing]'* the robot, which *'looks expensive'*, if they got involved in interacting with it. In addition, three passersby indicated that they felt unqualified to intervene in such situations, believing that professional assistance might be required. As exemplified by c10, who perceived the robot's *'flag waving around'* as not being directed at them, but *'some uni staff would be called there'* instead.

Triggers for engagement

As a bystander, completing the interaction sequence of assisting the robot involves two key motivational steps. First, they must be motivated to approach the robot and look into the peephole to assess the information about the robot's uncertainty. Second, they need to be motivated to offer help based on the information.

Curiosity and impacts of additional cues. Before accessing the information about the robot's uncertainty hidden behind the peephole, curiosity emerged as the primary motivating factor that led passersby to pause and approach the robot for closer observation (n=14). Six participants linked this curiosity directly to the peephole, as p18 noting that *'a combination of curiosity and fun-seeking nature'* led them to engage further by looking inside. Five participants suggested that the robot itself served as a trigger. Their motivation for getting closer to observe the robot was simply because they *'saw a large white box'* (p3) or believed the robot *'was stuck'* (p13). After the animated flag and audio cue were added, 12 participants mentioned that these cues attracted their attention and prompted them to stop and observe the robot. However, most of them (n=9) indicated they did not derive any underlying meaning of help-seeking from the cues beyond their attention-grabbing function. It is worth noting that participants only began to infer that the gestural cue was a request for help after the audio cues were added. As participants p24 and p25 specifically pointed out, it was the combination of the beep and the gesture that made them understand the robot's intent.

Care and contribution to robot learning. Once bystanders read the screen and understood that the robot was stuck due to uncertainty, some participants indicated that their helping behaviours were driven by empathy; for example, one participant stated they *'felt bad for it'* (p8). P1 further explained that this sense of care could be attributed to the peeping interaction, which brought them physically closer to the robot and lowered their height, fostering a more intimate engagement. P1 likened this mode of interaction to engaging with *'a puppy'*, which evoked a nurturing and caring response. Moreover, the sense of care can be attributed not only to the robot itself but also extended to the person associated with it, such as the service recipient or the robot's owner (n=2). For example, p17 suggested that their reason for offering help was out of concern that *'someone's delivery is going to be late'*. Beyond care, four participants mentioned that their motivation stemmed from the belief that their assistance could contribute to the learning and training of the algorithm driving the robot, thereby helping to improve its operational capabilities. As p2 suggested, *'Because it helps the robot to learn, so it can evolve faster.'*

Social influence. In addition to instances where bystanders engaged with the robot on their own initiative, we observed cases where passersby were influenced by the actions of others, which subsequently prompted further engagement. The interaction between bystanders and the robot often served as a catalyst, drawing additional attention from nearby individuals. For example, as shown in Fig. 9.5 (top), passerby B noticed group A interacting with the robot. This observation led passerby B to alter their path, approach the robot, and engage with it by looking into the peephole after group A left. Additionally, we observed that social influence played a role in encouraging further engagement with the robot, particularly in cases where hesitant passersby were influenced by others to interact. As depicted in Fig.9.5 (bottom), Group C initially stopped by the robot, engaging in observation and discussion. However, they hesitated to interact further. As they were about to leave, another group of passersby noticed the robot, prompting a conversation between the two groups. This exchange ultimately led both groups to collectively engage with the robot.

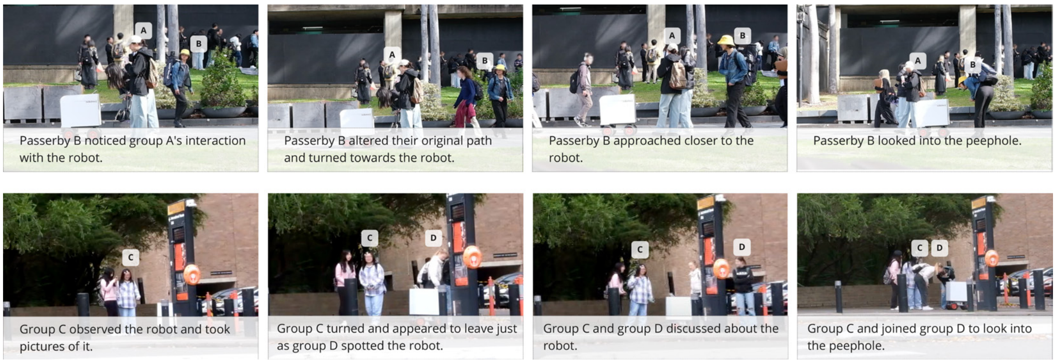

Fig. 9.5.: Social influence motivating bystander engagement: (Top) Passerby B approaches and interacts with the robot after observing Group A; (Bottom) Group C and Group D collectively engage with the robot after initial hesitation.

9.6.4 Impacts on bystander's attitudes towards robot

In this section, we report insights from post-interaction interviews on how involvement in the robot's uncertainty impacts people's perceptions and attitudes towards robots.

Human autonomy and control

We observed a trend in the interviews where participants seemed to feel empowered by maintaining control over the robot's autonomy, which may have contributed to these positive views. Nine participants expressed satisfaction they derived from assisting the robot having uncertainties, describing how it made them feel *'[the robot] being depended on [them]'* (p5, p9), *'important'* (p15), *'powerful'* (p22), and even *'superior to the robot'* (p22). Four participants, when discussing their intervention, interestingly remarked that as an indication that robots are yet not dominating, as p19 stated *'[it] shows me that they are not here taking over the world'* and *'it's a good sign that I'm still valuable, you know, as a human'*. Two participants expressed a preference for robots involving bystanders when facing uncertainties over fully autonomous robots, as they enjoyed the feeling of having *'control over it'* (p5), which even made them feel *'safer'* around the robot.

Connection through vulnerability and reciprocity

Five participants tended to anthropomorphise the robot when it communicated uncertainties, describing it as vulnerable entities, such as a *'kid'* (p15,16,18) or a *'little dog'* (p21) in need of help. Such perceived vulnerability contrasted with the typical stereotype of robots as perfect and infallible, instead highlighting more human traits. Four participants indicated that the robot seemed *'more human'* by acknowledging that these machines are not *'always correct'* but can *'also make some faults'* (p17). Two participants further noted that this vulnerability made the robot more *'approachable'* and *'affable'*.

Engaging with the robot during moments of uncertainty helped reduce the perceived distance between bystanders and the robot, fostering a sense of connection. As p6 stated, *'[...] normally for robots that operate autonomously, as a bystander, you normally don't have anywhere to interact with it'*, and they *'felt good [...] with this one, because it actually approached you and wanted some help.'* Additionally, five participants reported feeling *'closer to it (the robot)'* (p1) due to their interactions with the robot. P18 further described developing a *'personal connection'* with the robot, even as a bystander, attributing this to the casual collaboration that spontaneously formed during their encounter. Three participants mentioned the reciprocal nature of these casual collaborations, acknowledging that while the robot provides services to humans, a more *'symbiotic'* (p5) relationship is formed if humans also offer assistance when needed.

Trust

Although the objects that we staged for the robot to have trouble recognising were generally perceived as easy to identify, only one participant reported a decrease in their trust towards the robot. In contrast, six participants indicated that the robot's uncertainties did not significantly impact their trust. Interestingly, ten participants reported attributing even greater trust to the robot. This increase in trust was likely attributed to the perceived intelligence of the robot, as it was capable of acknowledging uncertainty and appropriately seeking assistance. As p11 suggested, they felt that the robot *'has the ability of independent thinking'*. Furthermore, five participants considered the robot's search for information during uncertainty as an essential part of its training process, enhancing its technological capabilities. This belief could also contribute to increased trust, as people perceived the robot as actively improving its performance. As p3 noted, *'it's trying to learn, like it's trying to get more data [...] once we give it an input, next time, when it faces the same problem, it can probably resolve it itself'*.

In addition to the perceived intelligence and belief in enhancing the robot's technological capabilities, the notion of *'being part of the process'* (p5) and thereby maintaining human autonomy in the robot's operation emerged as another reason for attributing trust, as indicated by three participants. The ability to intervene helped mitigate concerns about technology dominating, which could further enhance trust. As p19 suggested, *'I can see that it's not completely taking over the world. So it shows that the robot still needs the human side, and that improves the trust relationship'*.

9.7 Discussion

Drawing on the findings of the previous section, we first discuss the potential benefits and issues of involving bystanders in mitigating urban robots' technological imperfections. Reflecting on our design concepts, we further derive design implications for implicit and non-intrusive engagement strategies that encourage casual human-robot collaboration, supporting bystander participation in mitigating technological imperfections. These implications include *balancing bystander autonomy and persuasiveness*, *incorporating intentional friction to enhance engagement*, and *utilising robot gestural cues in public spaces*.

9.7.1 Involving bystanders in mitigating urban robots' technological imperfections

In the current debates regarding the impact of AI technology on human society, the *technology-centric view* (Peeters et al., 2021) suggests that AI will soon outperform humankind and eventually take over, potentially becoming the primary threat to humanity. Such concerns have influenced people's attitudes towards robots, leading to tensions about the introduction of robots into public spaces (Han et al., 2023; Bennett et al., 2021). A notable example occurred in San Francisco, where residents called for a ban on urban delivery robots shortly after their deployment (Guardian, 2017), driven by not only concerns about public safety, but also job displacement due to implications of automation.

This apprehension was also reflected in our field study, where some participants expressed concerns about fully independent robots in the interview. Interestingly, they indicated a sense of relief upon noticing the robot's uncertainty, viewing it as an indication that robots are not yet capable of total autonomy. They noted that the robot showing uncertainty demonstrated vulnerability, reassuring them that robots are not yet *'taking over the future'* (p5). By assisting the robot in navigating its uncertainty, participants felt empowered, reinforcing their sense of human superiority, as p22 described feeling *'powerful'* and *'superior to the robot'*.

While a robot's competence is often identified as a factor influencing people's social perceptions (Carpinella et al., 2017) and trust (Christoforakos et al., 2021) towards robots, our study revealed a different pattern. Instead of diminishing trust, nearly half of the participants reported an increase in trust towards the robot, despite it being stuck due to uncertainty. This can be partially attributed to the fact that bystanders were not direct service recipients, so the robot's uncertainty had little impact on them. More importantly, the increase in trust was likely tied to the autonomy and control participants maintained during the interaction. Keeping humans in the loop, even through simple actions like pressing a button to approve the robot's plan execution, has been shown to significantly enhance trust in the robot (Ullman and Malle, 2017).

Additionally, passersby's reactions of laughter and delight upon discovering the robot's uncertainty suggest their affection towards what people perceived as the robot expressing vulnerability, which they described as *'endearing'* (p19) and *'cute'* (p20). This affection is similar to previous findings in social robots, where people significantly preferred a robot making mistakes over a flawless one (Mirnig et al., 2017). While this study focused on humanoid robots with social capabilities and involved humans as collaborators, our findings extend this understanding. We show that affection towards a robot's mistakes can also manifest with a service robot designed for task execution rather than sociability, even in public spaces where bystanders have no prior relationship with the robot.

Our study demonstrates that the positive impact of maintaining human autonomy and allowing robots to display technological imperfections can extend beyond traditional human-robot collaboration settings (Schömbs et al., 2024; Hough and Schlangen, 2017; Moon et al., 2021) to public contexts, where humans engage as bystanders rather than collaborators. While commercially deployed urban robots increasingly come equipped with help-seeking features to request human assistance when facing physical limitations (e.g., getting immobilised due to obstructed road conditions) (Boos et al., 2022), these features often do not extend to situations involving technological imperfections, such as uncertainties in navigation decision-making. In such cases, robots still rely on remote human supervisors hidden in control rooms to resolve their uncertainties (Shaw, 2022), concealing the robots' struggles from the public. Our findings highlight the opportunity to engage bystanders' support in these moments of technological imperfection. This approach not only addresses the robots' operational challenges but also has the potential to alleviate public concerns (e.g., fears of technological domination) and foster closer relationships between urban robots and bystanders, ultimately promoting smoother integration of urban robots into everyday life. At the same time, however, exposing the robot's vulnerabilities could inadvertently place an unfair burden on the public, raising ethical concerns about the expectation of free labour (Dobrosovestnova and Reinboth, 2023). Furthermore, relying on bystander input introduces the risk of unreliable assistance, necessitating appropriate oversight mechanisms to ensure that bystander interventions do not compromise the robot's functionality.

9.7.2 Balancing bystander autonomy and persuasiveness

One noteworthy observation that emerged from our study was the low dropout rate once bystanders initiated interaction by peeking into the peephole, despite the overall limited engagement relative to foot traffic. In our study, only two out of 29 passersby who peeked into the peephole disengaged without offering further assistance. This stands in contrast to the study by Weiss et al. (2015), which investigated a similar scenario where a robot explicitly requested directions from passersby through verbal communication. In their study, out of approximately 100 robot-initiated interactions, only 36 participants completed the interaction by providing directions. Unlike their study, where participants were prompted by the robot's explicit verbal help-seeking request, the initiative taken by passersby in our study was rooted in intrinsic motivation, driven by human curiosity and playfulness in 'peeking'. This contrast illustrates the principles of ludic engagement, where the peephole's openness and ambiguity subtly invite bystanders' exploration without explicitly compelling engagement, leading to deeper and more self-motivated involvement.

Furthermore, this can be understood through the lens of self-determination theory (Ballou et al., 2022; Ryan and Deci, 2018), which suggests that when individuals initiate actions themselves, they experience enhanced autonomy, leading to deeper intrinsic motivation. As a result, they are more likely to commit to continuing the interaction due to a sense of ownership over the action. This theory has been applied in HCI to address interaction motivation across domains such as learning (Dhiman et al., 2024), game design (Tyack and Mekler, 2020), and human-robot interaction (Minkelen et al., 2020).

While bystanders were more likely to continue their involvement and offer help when they took the initiative, our study also reveals barriers for bystanders in initiating interactions with a robot they had no pre-existing relationship with, as reflected in the overall limited engagement relative to foot traffic. Even when they had the intention to interact, bystanders often hesitated, perceiving the robot as someone else's property rather than something that they could freely engage with. This perception may account for our observation of passersby often looking around, seemingly searching for a person 'in charge' when they noticed the robot in need of assistance. This suggests that before bystanders can transition from passive observers to active collaborators, the robot must provide a clear signal of openness, essentially granting permission for further interaction.

The barriers led us towards design decisions of adding additional cues to 'nudge' bystanders into engaging with and helping the robot. This effort to enhance engagement surfaced a tension: our aim to uphold bystander autonomy through non-intrusive design conflicted with the potential risk of crossing into manipulative territory. This tension resonates with broader concerns in HCI regarding the use of design power (Kender and Frauenberger, 2022) and the implementation of dark patterns (Lacey and Caudwell, 2019; Mathur et al., 2021) to manipulate user behaviours. Such concerns become especially pertinent in the context of bystanders assisting commercially deployed robots, where the persuasiveness of these design strategies could lead to issues of invisible labour and potential exploitation (Dobrosovestnova and Reinboth, 2023). Thus, careful consideration must be given to balancing bystander autonomy and the persuasiveness of engagement strategies.

9.7.3 Incorporating intentional friction to enhance engagement

Unlike common interaction design principles that tend to emphasise ease of use (Rogers et al., 2011), our design concept introduced a level of friction, requiring passersby to bend over or even squat to peek through a small peephole to access information and proceed with the interaction. The low dropout rate suggests that these physical barriers did not deter passersby from further engagement; instead, the added physical challenge unexpectedly appeared to enhance their sense of involvement. This aligns with the concept of psychological ownership (Pierce et al., 2003), which suggests that effort invested in an object or task increases individuals' sense of ownership and personal connection, motivating deeper engagement and commitment. The observation of bystanders lingering and waiting for the robot to resume movement further demonstrates this commitment, suggesting that their continued presence reflects a sense of care (Dobrosovestnova and Reinboth, 2023) developed through the interaction.

Design frictions refer to points of difficulty encountered during a user's interaction with technology, which are often minimised to increase and sustain user engagement with a product (Cox et al., 2016). However, Cox et al. (2016) argue that incorporating friction can prompt reflection and foster more mindful interaction. This approach has been used to reduce input errors (Wiseman et al., 2013) and promote behaviour change, such as reducing smartphone distractions (Dutt et al., 2024). While design friction is often used to discourage certain actions, our study shows it can also be utilised to motivate deeper bystander involvement by increasing their physical investment in interactions. When designing for voluntary, casual human-robot collaboration, designers could consider introducing intentional friction into interactions, where the challenge itself becomes a driver for continued involvement.

9.7.4 Utilising robot gestural cues in public spaces

The introduction of gestural cues (i.e., the animated flagpole) did not significantly increase the number of passersby who paid attention, nor did it raise the percentage of individuals who paused for further engagement. While previous research suggests that humans tend to perceive non-verbal gestures from non-humanoid robotic objects as social signals (Novikova and Watts, 2014; Erel et al., 2022; Erel et al., 2024; Press and Erel, 2022; Chakravarthi Kumaran et al., 2024) that invite further interactions (Ju and Takayama, 2009; Sirkin et al., 2015b), our study revealed gaps in transferring this effectiveness to public spaces. This could be explained by the contextual complexity of public spaces and the casual nature of the setting, where people without a pre-determined intention to interact may not interpret such cues as invitations for further interaction.

Passersby's attention is often fragmented. Based on our observations, most passersby offered only brief attention to the robot, often limited to a quick glance, making it difficult for them to grasp the full context of a motion sequence and infer its underlying meaning. In addition, previous studies of gestural cues were often conducted in controlled lab settings where participants were primed with context to observe and interpret the robot's behaviour. In contrast, random passersby in public spaces lack this contextual framing, making it difficult for them to interpret the meaning of the robot's gestures. The study most comparable to ours is (Ju and Takayama, 2009), where authors observed passersby's spontaneous reactions to an automated door's gestures (e.g., different movement trajectories) in a field setting. The study found significant uniformity in participants' interpretations, perceiving the door's gestures as conveying different approachability. However, in this study, passersby intended to pass through the automated door, making attention to the door's gestures an inevitable step before they could proceed with their primary goal. In contrast, in our study, the robot's gestural cues were completely irrelevant to the activities that bystanders were engaged in.

Interestingly, after the auditory cue was added, a noticeable shift occurred: participants began to infer that the gestural cues were communicating a need for help, interpreting this through the combination of auditory and gestural signals. This contrasts with participants' perception of the animated flagpole, which, prior to the audio cue being added, was seen as having no communicative intent beyond greeting or attracting attention.

Our findings suggest that passersby's fragmented attention and the lack of contextual framing in public spaces can make the nuances in robot gestural cues difficult to grasp. Designers should consider limiting the complexity of such cues to basic functions, such as attracting attention or supplementing them with other signals, such as audio, to provide more contextual information and enhance communication effectiveness.

9.7.5 Limitations

First, our field study took place on a university campus, where students comprised the majority of passersby. This context may have influenced the nature of interactions, limiting the transferability of our findings to other public spaces with different demographic compositions. Second, the evolving nature of our design concept and the variation in deployment locations introduced complexities that shaped our observations and insights, making it challenging to achieve traditional data saturation (Braun and Clarke, 2021). This is due to our study following an RtD approach (Zimmerman et al., 2007), which emphasises iterative, exploratory processes where insights evolve throughout the research. This epistemological stance shifts the focus from traditional saturation to capturing the reflectiveness and relevance of insights, which we ensured by meticulously documenting the evolution of our design concepts and articulating the insights generated throughout the iterative process and field study.

9.8 Conclusion

This study approached the challenge of urban robot uncertainty from a novel angle, moving beyond purely technological advancements to actively engage bystanders as participants in mitigating robot uncertainty. We designed a speculative *peephole* concept that invites bystanders to help resolve the robot's uncertainty in a non-intrusive, curiosity-driven manner. The concept was tested in a field study to probe passersby's spontaneous reactions and examine how their involvement shaped their perceptions and attitudes towards the robot. Despite the low overall engagement relative to the foot traffic, we observed a strikingly low dropout rate among those who took the initiative to engage with the peephole, with many expressing genuine enjoyment from the interaction. At the same time, a sense of empowerment, affection, and connection towards the robot emerged as bystanders helped the robot resolve its uncertainty.

Drawing on these findings, we highlight the potential of involving bystanders to mitigate urban robots' technological imperfections, which can not only address operational challenges but also foster public acceptance of robots. Furthermore, our reflections on the design concepts offer practical design implications that designers can leverage to support bystander engagement with urban robot technological imperfections. These include balancing bystander autonomy and persuasiveness, incorporating intentional friction to encourage deeper engagement, and the use of robot gestural cues in public spaces. While speculative in nature, our concept served as a vehicle for knowledge generation, providing insights on how to engage bystanders in urban robot uncertainty while minimising intrusiveness. We hope that our work lays a valuable foundation for future studies to build on these implications and develop practical solutions, facilitating the seamless integration of urban robots into everyday life and fostering symbiotic human-robot relationships.

Part IV

Discussion

Discussion

10

10.1 Preamble

This chapter begins by addressing the three core research questions (RQs) that guided this doctoral investigation: firstly, the situations and design opportunities of casual human–robot collaboration (RQ1); secondly, the design of interactions that can facilitate such collaboration (RQ2); and lastly, how bystanders perceive, interact with, and make sense of casual collaboration with urban robots (RQ3). This is followed by a synthesis and reflection of the key insights drawn from the empirical studies, through which I provide a conceptualisation of casual human–robot collaboration: collaboration as the *balancing of human-robot spatial rights*, as the *bridging of robot–environment misalignments*, and as the *emergence of distributed autonomy*. The chapter then presents a reflective evaluation of the doctoral research by critically examining its methodological rigour against the criteria for evaluating Research through Design proposed by Zimmerman et al. (2007). At last, the chapter outlines potential areas for future work.

10.2 Answering the Research Questions

The first chapter introduced the core research questions of this doctoral research. These questions are revisited in the following sections, with each subsection dedicated to one specific question. The corresponding answers and contributions are highlighted and discussed. For a concise overview, see Table 10.1.

Tab. 10.1.: The research questions, the chapters that address them, the answers to the research questions as supported by the chapters, and the corresponding contributions

Research Question	Chapters	Answer	HCI Contribution
RQ1: In what situations does casual collaboration between urban robots and bystanders unfold? What design opportunities are emerging from these situations?	2, 3	• **Path negotiation:** Bystanders and robots navigate narrow or intersecting routes together, requiring collaborative adjustments to avoid collisions and ease passage. • **Physical incapabilities:** Mismatches between robot capabilities and the built environment can hinder their operation and mobility. • **Technological limitations:** Uncertainty is inherent in the autonomous decision-making processes of robots, which can lead to undesired outcomes.	**Empirical Contributions**: Identifying situations and design opportunities for casual collaboration that are grounded in real-world encounters with urban robots.
RQ2: How can we design interactions that facilitate casual collaboration between bystanders and urban robots?	3 - 8	• Achieving transparency through interaction. • Promoting bystander-initiated participation. • Curating playfulness as engagement incentive. • Leveraging intentional friction.	**Artefact Contributions**: A series of design artefacts and the documentation of the design process. **Empirical Contributions**: Empirically validated design recommendations and implications.
RQ3: How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?	4, 6, 7, 8	• **Perception**: Perceiving robots as approachable yet competent. • **Interaction**: Engaging through care, exploration, and playfulness. • **Sense-making**: Cultivating trust and acceptance through shared agency.	**Empirical Contributions**: Understanding of how bystanders perceive, interact with, and interpret casual collaboration with urban robots.

10.2.1 Research Question 1: In what situations does casual collaboration between urban robots and bystanders unfold? What design opportunities are emerging from these situations?

By synthesising insights from empirical encounters gathered through online ethnography (Chapter 3) and urban robot contextual adaptability issues elicited through design probes (Chapter 4), we identified the following situations in which casual collaboration between urban robots and bystanders unfolds, together with the corresponding design opportunities:

- **Human-robot spatial conflicts.** Urban robots often operate in close proximity to people, such as when sharing sidewalks. These situations create moments where bystanders and robots must navigate narrow or intersecting routes together, requiring collaborative adjustment to avoid collisions or ease passage. This highlights the design opportunity for interfaces that facilitate smooth co-navigation, making robots' intentions clearer and supporting mutual coordination.

- **Robot-environment misalignments.** Urban robots are introduced into city environments that have been primarily designed for human use, which often creates mismatches between their capabilities and the built infrastructure (e.g., pressing traffic-light buttons, climbing stairs). At the same time, dynamic features of the urban environment, such as parked bicycles, rubbish bins, or crowds, can block their movement. These situations not only hinder urban robots' operation but can also disrupt the surrounding environment. They highlight design opportunities for interfaces that enable robots to communicate their limitations and to invite bystander assistance in a socially appropriate manner.

- **Robot technological limitations.** Uncertainty is inherent in the autonomous decision-making processes of robots, and this challenge becomes especially pronounced in urban environments. Such uncertainty can lead to undesired behaviours that not only hinder urban robots' operation but also create risks for people and the surrounding space. These situations highlight design opportunities for interfaces that enable robots to reveal their uncertainties to bystanders and to involve them in resolving the situation.

10.2.2 Research Question 2: How can we design interactions that facilitate casual collaboration between bystanders and urban robots?

Through the development and exploration of several design concepts that addressed casual collaboration in the situations described above, a set of common design implications emerged, which we conceptualise and articulate as follows:

Transparency through interaction. Transparency has long been considered an important factor in interactions with machine autonomy (Lyons and Havig, 2014), often framed as the communication of information from the system to people in order to facilitate interaction and foster trust. For two of the concepts developed in this work, the *pedestrian path prediction visualisation* (Chapter 5) and the "*Peephole*" (Chapter 9), transparency was not limited to the passive reception of information. Instead, it became something that bystanders could actively participate in and influence. This was exemplified in people's exploratory behaviours when engaging with the *pedestrian path prediction visualisation*, such as deliberately altering their path to test the robot's reactions. With the *Peephole*, this exploratory stance surfaced as excitement when passersby realised they could intervene in the robot's behaviour during moments of uncertainty. These findings suggest that transparency communication can be designed as an interactive process, where people are invited to engage with and even probe the robot's autonomy.

Promoting bystander-initiated participation. The design workshop in Chapter 6 and the comparative study of different robot help-seeking strategies in Chapter 7 indicated that the unique context of bystander casual collaboration creates new interaction requirements that differ from traditional human–robot collaboration. Without a pre-existing relationship and without a shared task, the strategies typically used to engage people, such as direct verbal communication (Dobrosovestnova and Reinboth, 2023; Cameron et al., 2015), can become less effective or even socially inappropriate. As demonstrated in Chapter 7 and Chapter 8, explicit verbal requests could be perceived as impolite and overly demanding in spontaneous public encounters. Thus, mediating casual collaboration between bystanders and urban robots should draw on implicit and non-intrusive approaches (e.g., the *peephole* concept in Chapter 9), presenting involvement as a voluntary and spontaneous act that encourages initiative from the bystanders themselves, rather than as an obligation implied by direct verbal requests.

Playfulness as engagement incentive. Bystanders who do not directly benefit from urban robot services often require a form of incentive to invest their time and effort in interacting with robots they encounter casually. As validated in this work, playfulness can serve as such an incentive, and it can be utilised either in a more direct way, by incorporating game-inspired elements as in Chapter 7, or in a more ambient form, such as the *Peephole* concept in Chapter 9, where the engagement of bystanders was promoted through their own curiosity. Furthermore, self-motivated involvement triggered by playfulness can lead to higher commitment in completing the interaction. This was supported by the sustained willingness of participants to assist robots even as the physical demands of helping increased (Chapter 7), and by the low drop-out rate observed in the field study once passersby decided to peek into the box (Chapter 9). This quality is particularly valuable for casual collaboration, as bystanders do not have a predetermined task to complete and their participation cannot be secured through imposed obligations.

Leveraging intentional friction. The approaches explored in this thesis to engage bystanders in casual collaboration did not prioritise efficiency of interaction as the primary goal. Instead, some concepts introduced a degree of additional friction into the interaction. For instance, the game-inspired help-seeking in Chapter 7 required participants to complete a game that involved extra actions in order to assist the robot, while in Chapter 9 people had to physically bend down and peek through a small lens to access information about the robot's uncertainty. Such friction, while adding difficulty, can motivate deeper bystander involvement by increasing their physical and cognitive investment in the interaction. At the same time, given the rapid and often fleeting nature of casual encounters, such friction must remain succinct and flexible, accommodating the varying preferences, time, and effort that bystanders are willing to contribute.

10.2.3 Research Question 3: How do bystanders perceive, interact with, and make sense of casual collaboration with urban robots?

Perceiving robots as approachable yet competent. The lab studies and the field deployment reflected a generally positive attitude toward casual collaboration with urban robots. The robots' imperfections and their need for human help made them appear more approachable and emotionally engaging. However, at the same time, because urban robots are often perceived as belonging to the societal category of service providers, their ways of involving people also need to convey a sense of proficiency and competence, rather than displaying excessive neediness or helplessness. These findings suggest that imperfection and vulnerability, when carefully designed, can function as positive social cues that make robots feel less distant and more relatable, easing the perceived divide between human and machine and fostering emotional accessibility in casual encounters.

Engaging through care, exploration, and playfulness. Bystanders' engagement with urban robots was motivated by both intrinsic and extrinsic factors. Intrinsically, people were driven by a sense of care toward both the robots themselves and the people who receive service from the robots. In situations involving robot uncertainty, casual collaboration was also motivated by a belief in supporting technological advancement, as people regarded their involvement as a contribution to helping robots learn or improve. Extrinsically, engagement was stimulated by the design of the interfaces, which sparked curiosity and invited participation through elements of playfulness. Subtle prompts and interactive affordances, ranging from practical features such as path prediction visualisations (Chapter 5) to more ludic concepts like gamified help-seeking (Chapter 7) and the "Peephole"(Chapter 9), encouraged bystanders to approach, explore, and improvise, transforming casual encounters into moments of participation and discovery.

Cultivating trust and acceptance through shared agency. Casual collaboration generally fostered a sense of trust and acceptance toward the robots, which is not based solely on the technical capability of robots. Rather, it emerged through the dynamics of shared agency in which both human and robot contributed to resolving the situation. On one hand, bystanders recognised the robot's capacity to strategically involve humans when facing limitations, which demonstrated a form of situational intelligence and adaptability. On the other hand, people's ability to intervene and influence the operation of robots allowed them to maintain a sense of autonomy and control within the interaction. This balance between reliance and participation shaped trust as a mutual and negotiated relationship, rather than a one-sided dependence on the technical reliability of robots. At the same time, however, the casual collaboration also prompted ethical considerations around invisible labour, raising questions about whether the voluntary assistance from bystanders might, over time, become an unacknowledged contribution that sustains the functioning of autonomous systems in urban space. These concerns highlight the need for future designs to remain sensitive to how such collaborations distribute effort and responsibility in shared public spaces.

10.3 Framing Casual Human–Robot Collaboration in Urban Public Spaces

Drawing together insights from the empirical studies presented across this thesis, alongside the answers to the research questions outlined in the previous section, a renewed understanding of human–robot collaboration in public urban environments begins to emerge. In the sections that follow, I outline three ways to conceptualise casual human-robot collaboration (see Fig. 10.1 for an overview): collaboration as the *balancing of human-robot spatial rights*, as the *bridging of robot–environment misalignments*, and as the *emergence of relational, distributed autonomy*. Each subsection begins by describing the human–robot–environment entanglements that give rise to the different forms of collaboration, providing HRI researchers with analytical lenses for interpreting everyday encounters with robots in urban public spaces and identifying opportunities where new forms of collaboration can be cultivated. These conceptualisations also offer designers, roboticists, and urban planners a way to incorporate casual collaboration into the design and deployment process of urban robots, supporting the development of systems and infrastructures that more deliberately accommodate such situated forms of human–robot collaboration. Then each subsection discusses how design can shift in how these situations unfold, moving from *robot compliance to shared resolution*, from *peripheral help toward situated co-engagement*, and from a *closed service ecology toward distributed autonomy*. This offers practical guidance for designers and HRI researchers in shaping interaction strategies grounded in mutual dependence and reciprocity, rather than positioning robots as deferential, low-status service agents or as distanced, technological artefacts.

10.3.1 Human–robot collaboration as the balancing of spatial rights.

Asymmetries in spatial rights.

The simplest and most common forms of casual human–robot collaboration arise in the moment-to-moment negotiations that occur when people and robots move through shared spaces. In everyday urban settings, humans routinely make small adjustments, shifting their trajectory, stepping aside, slowing down, or briefly pausing, to accommodate the movements of others. When an urban robot enters these environments, it becomes part of this ongoing choreography (Pelikan et al., 2024; Yu et al., 2024c).

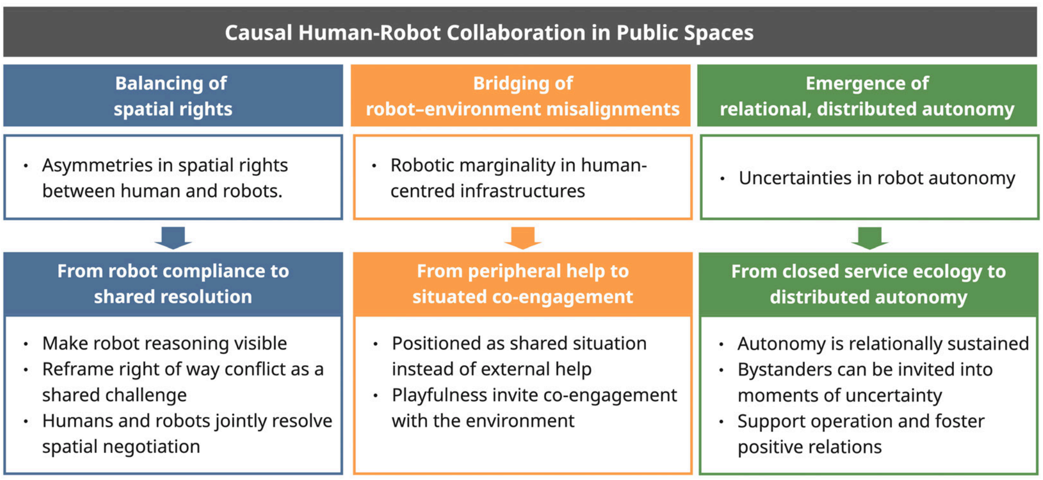

Fig. 10.1.: Overview of conceptual framings of casual human–robot collaboration in urban public spaces

When spatial rights come into conflict, the negotiation of space between people and robots is not merely a matter of physical avoidance. Instead, it is deeply shaped by social expectations surrounding priority, politeness, and entitlement to shared resources. Robots are frequently attributed lower social roles, such as assistants, tools, or servants (Dautenhahn et al., 2005; Walters et al., 2012), and this positioning produces a power asymmetry. This social positioning leads people to expect that robots should be polite and submissive during conflicts (Babel et al., 2024; Babel et al., 2022a), and assume that their own spatial rights should take precedence. For example, Babel et al. (2024) examined a scenario in which a robot and a human arrived at an elevator at the same time, and found that participants evaluated the robot negatively when it asserted priority by entering first.

These expectations are not only enacted socially but also encoded technically in how mobile robot navigation systems are designed. Human intention prediction has become an essential component of navigation decision-making, enabling robots to anticipate people's movements and adjust their own trajectories accordingly (Rudenko et al., 2020). By inferring human intentions, robots can reroute, slow down, or wait in order to minimise disruption and maintain socially acceptable behaviour. However, such deference comes with trade-offs. Constantly yielding to humans can reduce operational efficiency and compromise service quality (Jennings and Figliozzi, 2019), particularly for urban robots that perform time-sensitive tasks such as delivery.

From robot compliance to shared resolution.

In this thesis, two studies attempted to address the tension between spatial rights conflicts and navigation efficiency, but from opposite directions. The study in Chapter 5 made the robot's prioritisation logic visible to bystanders by visualising both the predicted path of pedestrian and the robot's corresponding planned trajectory, revealing how it interpreted human movement and adjusted its own behaviour. This path prediction visualisation externalised the robot's compliance with the human–robot power asymmetry in spatial negotiation and was intended to support mutual understanding and, in turn, improve navigation efficiency. However, the study revealed unintended consequences. Several participants reported feeling obliged to follow the predicted path, as if the robot had already outlined the correct way for them to move or had subtly "claimed" the spatial right-of-way.

In contrast, the Tetris-inspired concept explored in the pedestrian-blocking scenarios in Chapter 7 approached the problem from the opposite direction. Rather than communicating the robot's compliance, the robot asserted its own need for space and asked bystanders to make way. Moreover, instead of relying on politeness strategies that are a common approach to resolving human–robot conflicts (Babel et al., 2021), the gamified concept reframed the right-of-way problem as a collective challenge that the robot and human needed to resolve together. This shifted the focus away from the question of *"who has the right"* and instead transformed the situation into a shared interaction rather than a contest over precedence. Contrasting these two approaches offers a new perspective on human–robot spatial rights conflicts. What is often treated as an uneven situation in which robots must constantly defer to humans can instead be reframed as a more balanced form of collaboration through design, where both humans and robots actively contribute to resolving the conflict.

10.3.2 Human–robot collaboration as the bridging of robot–environment misalignments

Robotic marginality in human-centred urban infrastructures.

The urban landscape is fundamentally designed for human use and has become relatively fixed over time. Much of its present form was shaped in the twentieth century, when personal vehicles and public transportation replaced horse-drawn carriages to meet growing human mobility needs (Chiu, 2008), and was gradually layered with affordances such as curbs, steps, narrow footpaths, and hand-operated traffic-light buttons that are designed to cater to human capabilities and everyday activities.

For robots, however, these mundane features can become significant obstacles. As the online ethnography in Chapter 3 illustrates, a curb that is trivial for a pedestrian can become an impassable barrier; a tree pit on the sidewalk can easily trap a robot; and a traffic-light button that humans can press effortlessly can leave a robot waiting indefinitely at a crossing. The fact that most public infrastructure is not "robot-ready" has been widely recognised as one of the most pressing barriers to the large-scale deployment of service robots such as delivery robots (Xia and Yang, 2018; Hossain, 2023). Recognising these challenges, Franchi et al. (2025) developed the *Robotability* score, a quantitative tool for evaluating how navigable different urban spaces are for robots, in order to guide the efficient deployment of robots. Although some researchers have proposed modifying city infrastructure to better accommodate automated systems (Liu et al., 2023), such infrastructural interventions are often costly, slow to implement, and difficult to scale.

To address the constraints on urban robot operation caused by robot–environment mismatch, one common strategy is robotic enhancement. Engineering work has focused on designing more capable robots that can physically overcome common urban obstacles—for example, eight-wheeled delivery robots capable of climbing curbs (Kaya and Erdemir, 2023), legged robots that emulate aspects of human mobility to better adapt to human-centred urban spaces (Kotha et al., 2024), or hybrid solutions that combine vans with small delivery robots to bridge segments of the environment that robots cannot yet traverse (Ghiani et al., 2025).

While such approaches offer important technical solutions, they implicitly cast robots as machines that must adapt to the city rather than as participants within it. Franklin (2017) argues that cities are never purely human spaces but dynamic assemblages of humans, infrastructures, and more-than-human actors, including technologies such as robots. Solely pursuing technological enhancement risks further distancing robots from the people and communities they are meant to coexist with, reinforcing a model of separation rather than interdependence. Lupetti et al. (2019) introduces *robot citizenship* as a design perspective that shifts attention away from perfecting robotic self-sufficiency and toward relationality and interdependence. This relational perspective motivated the investigations in this thesis, exploring how humans can be involved when robot–environment misalignments hinder robotic operations.

From peripheral help to situated co-engagement with the environment.

The playful design concepts in Chapter 7 reconfigure the human's role in moments of robot–environment misalignment. In conventional framings, humans stand outside the robot–environment relationship and are mobilised as external helpers when the robot becomes stuck. This is reflected in conventional approaches that rely on explicit communication channels such as spoken language to request assistance (Cameron et al., 2015). Such approaches implicitly frame the misalignment as a problem that belongs solely to the robot, thereby rendering humans peripheral to the situation and positioning them merely as optional helpers rather than participants in a shared encounter. This peripheral positioning reinforces the sense that bystanders are not obligated to respond and makes verbal help-seeking feel overly directive, with people often interpreting the robot as giving orders, which led to discomfort or reluctance to assist.

The playful design concepts in Chapter 7 take a fundamentally different approach. Rather than framing the moment as a robot breakdown that demands human assistance, they overlay gamified visual content directly onto the infrastructure that hinders the robot (e.g., transforming the pavement into a Space-Invader–like interface in which the traffic-light button becomes the trigger for "shooting"). In doing so, the locus of the issue shifts: what was previously understood as a dyadic problem between robot and environment is reconfigured as a situated entanglement of robot, human, and environment. The misalignment is recast as a shared, co-present challenge embedded in the materiality of the city, inviting bystanders into a playful form of joint engagement rather than positioning them as external helpers. In reframing misalignment as a shared, situated engagement, these designs operationalise the relational perspective introduced above, treating humans not as external problem-solvers but as co-present actors within an unfolding human–robot–environment ecology.

10.3.3 Human–robot collaboration as the emergence of relational, distributed autonomy.

Uncertainties in robot autonomy.

Autonomous decision-making is fundamentally uncertain (Leusmann et al., 2023), and this uncertainty becomes especially pronounced in dynamic urban environments. Current commercial service-robot deployments typically address such technological breakdowns by relying on remote teleoperators who intervene invisibly in the background (Ghiani et al., 2025). While teleoperation ensures operational continuity, it also reinforces a strict separation between robots and the people around them, positioning those physically co-present humans as irrelevant to the immediate ecology of the robot's functioning.

The ecological perspective proposed by Dobrosovestnova et al. (2025) challenges this separation by showing that robot operation is not sustained through a *service ecology* of remote operators, maintenance staff, fleet managers, but also as the *street life ecology* in which robots move and encounter people. In this view, urban robot autonomy is not achieved and maintained solely by the service provider but emerges through the situated, distributed actions of multiple actors in the urban environment.

Operationalising this perspective through design practice, this thesis understands moments of uncertainty not as isolated technical failures that service providers are responsible for, but as events that unfold within street-level ecologies where nearby people could play a meaningful role in sustaining the robot's functioning. I frame this as distributed autonomy—autonomy that is not accomplished by the robot's technical capabilities alone, but is relationally sustained across the robot and nearby people. It shifts attention away from treating autonomy as a self contained technical property of the robot, and towards the broader sociotechnical relations that enable the robot to function in practice. The final empirical study of this thesis (Chapter 9) explores this possibility by investigating how passersby might be invited into these moments of uncertainty. The findings show that such moments of engagement can not only support the robot's immediate operation, but also foster more positive and socially engaged relations between robots and bystanders.

From closed service ecology to distributed autonomy.

The shift from a closed service ecology to a more distributed form of autonomy that involves collaboration with bystanders introduces new challenges. In contexts where humans operate together with machines, such as operators working with robots or drivers supervising autonomous vehicles, people share a close spatial, perceptual and psychological alignment with the system. They monitor the machine continuously, understand its operating context and remain ready to intervene when uncertainty arises. This section outlines the distances that arise along these three dimensions and discusses how design can help narrow them to support casual collaboration in moments of robot uncertainty.

Physical distance. When an urban robot, especially non-anthropomorphic ones with limited expressive capabilities, encounters uncertainty or becomes stuck, passersby are often not in a physical position where they can easily notice the situation. People are typically taller than the robot and move through the space from higher or shifting vantage points, occupying spatial perspectives that make it difficult to discern what the robot is struggling with. This contrasts with operators in other contexts, for example, drivers in autonomous vehicles, who share the same embodied viewpoint as the machine and can more readily perceive when intervention is needed. The *peephole* concept in Chapter 9 addresses this challenge by using a small aperture that invites people to move closer, lean in, and lower themselves to the robot's height. This act of approaching and aligning one's viewpoint with the robot collapses the physical distance, enabling bystanders to become attuned to the robot's perspective.

Perceptual distance. Unlike operators of other automated systems who possess domain knowledge about the system, bystanders in public space have little understanding of how a robot operates or what kind of assistance it may require. This makes it important to present uncertainty information in an intuitive, easily interpretable form and to simplify the input needed from bystanders. The *peephole* concept in Chapter 9 directly overlays uncertainty information onto a camera-view image of the robot's sensed environment, revealing what the robot "sees" in a way that is immediately relatable to humans. In addition, it minimise the required input to a simple yes/no judgement that can be expressed through natural language spoken input, an interaction that requires no prior expertise and has become increasingly accessible and flexible with recent advances in large language models.

Psychological distance. Even when bystanders are physically close to a robot and able to perceive its difficulty, the study in Chapter 9 shows that they may still experience a form of psychological distance. This distance emerged either from people's doubt in their own capacity to assist, assuming that robots were technologically complex and that intervention required specialised knowledge, or from a perceived lack of authorisation to act, as people viewed the robot as property that outside their legitimate sphere of responsibility. The *peephole* concept addresses the first form of psychological distance by revealing the robot's uncertainty through a low-tech, analogue-feeling invitation mechanism. Its familiar, mundane form shifts people's assumptions away from high-tech complexity, lowering the psychological boundary and making the uncertainty situation feel more approachable. The second form of psychological distance, the sense of lacking authorisation, which emerged in the study, however, remained unaddressed by the design. This limitation points to a deeper sociotechnical issue around the ownership and governance of public robots that requires further work not only in interaction design but also in how responsibilities and rights are distributed among service providers and the public.

10.4 Reflective Evaluation of the Research

Zimmerman et al. pointed out that in Research through Design, the quality of the contribution rests less on the expectation of replicable outcomes and more on the rigour with which methods are applied, the rationale for their selection, and the extent to which the process is documented for others to retrace (Zimmerman et al., 2007). In this section, I reflect on this doctoral research against the criteria for evaluating Research through Design research proposed by Zimmerman et al. (2007), which encompass four aspects: process, invention, relevance, and extensibility.

10.4.1 Process - How well were the methods justified and applied, and was there enough detail to reproduce the process?

This doctoral research employed a multi-method approach, beginning with an online ethnography into real-world deployments of urban robots (detailed in Chapter 3). This stage grounded the research in the lived realities of people's interaction with urban robots in public spaces and provided a foundation for subsequent design investigations. An **online ethnography**, a well-established method in HCI and HRI for examining public interactions and perceptions of technology, was conducted using user-generated videos on social media that captured spontaneous encounters with urban robots. To ensure the robustness of this dataset, a set of inclusion criteria and a systematic screening process were developed and applied, supporting both the authenticity and the validity of the video material. We then meticulously documented the screening and analysis process, including the development of a codebook through an iterative procedure involving multiple coders, which guided the systematic interpretation of the data.

To bridge the insights from these real-world observations with potential design solutions for facilitating casual human–robot collaboration, a series of design workshops were conducted. These workshops employed **bodystorming** methods, in which participants enacted scenarios of casual human–robot collaboration, taking on the perspective of either the human or the robot. Immersing people directly into the perspective of robots can foster a heightened sense of bodily empathy in the design process of human–robot interaction. This approach was particularly well-suited to this doctoral research, which investigates the complex socio-technical dimensions of casual human–robot collaboration in public urban contexts. A detailed documentation of the role-play bodystorming activities, including the use of physical probes, the scenario set-up, and the procedure, was provided, accompanied by a clear account of the analysis process showing how insights from these activities were translated into design knowledge.

The design concepts that were created were subsequently prototyped and evaluated in two complementary settings: **controlled VR lab studies** and an **in-the-wild field study**. VR lab studies, a commonly used method in HRI for evaluating interactions, provided controlled conditions for systematically examining specific aspects of human–robot interaction. However, given the spontaneity of casual collaboration investigated in this research, the artificial nature of the lab setting risked limiting the authenticity of people's reactions and perceptions. To address this, the in-the-wild study enabled the observation of more authentic, situated responses. Together, the VR lab studies and field study played complementary roles in the research process: the former enabled controlled examination of interaction mechanisms, while the latter captured the situated complexity and unpredictability of real public environments, complementing the lab-based findings with greater ecological validity and strengthening the overall robustness of the research process.

10.4.2 Invention - How does the research contribute to the work already in the research community?

The invention of this work lies in three main aspects. Conceptually, it frames casual, unplanned collaboration as a meaningful dimension of human–robot collaboration, moving beyond instrumental or task-based engagements towards spontaneous, situated encounters. This conceptualisation offers a new perspective on robots by shifting the view from purely technological affordances to their operation as a form of mutual dependency between robots and bystanders.

Empirically, the lab studies and in-the-wild deployment that probed such casual collaborations indicated that they can foster more positive attitudes towards robots and enhance trust. This provides evidence that designing for casual human–robot collaboration has the potential to contribute to greater social acceptance and to support the integration of robots into everyday urban environments. These results extend HRI research by positioning trust and acceptance not only as matters of reliability and safety but also as outcomes of relational, situated interaction.

Practically, the work proposes a set of design considerations and exemplars that illustrate how casual collaboration can be intentionally supported in practice. Through the research through design process, playfulness has emerged as a recurring theme and was explored as a strategy for encouraging bystander engagement. Such playfulness was manifested in different forms, ranging from approaches that directly integrated gamification into the interaction (Chapter 7), to the concept that rendered playfulness in more implicit and ludic modes of engagement (Chapter 9). By incorporating playfulness as both a design strategy and an experiential quality, this research contributes to HRI by extending existing work on playful interaction with robots, which has largely focused on domains such as entertainment (Hoggenmueller et al., 2020b), education (Heljakka et al., 2019), and therapeutic contexts (Kozima et al., 2009). It demonstrates that playfulness can also function as a mechanism for fostering casual, prosocial collaboration in public urban spaces, thereby broadening the ways in which play is understood and applied within HRI.

10.4.3 Relevance - How is the work relevant, and what motivation and preferred state does it articulate?

This doctoral research is motivated by the growing presence of robots in public urban environments, where they are increasingly deployed to provide everyday services such as delivery, mobility support, and public service. While these robots are primarily designed to fulfil these functional tasks, in practice, they spend much of their operational time roaming through streets and shared spaces, where they encounter passersby who are not their intended users are largely overlooked in the design process. These incidental encounters raise questions about how robots can coexist with the public in ways that go beyond efficiency and functionality, and how such moments might be reimagined as opportunities for meaningful engagement rather than sources of friction.

This research therefore articulates a preferred state in which urban robots are not only efficient service providers that share urban spaces with humans, but also socially embedded actors that can cultivate moments of delight and foster reciprocity in their everyday encounters with bystanders. This aligns with emerging viewpoints in HRI that re-envision robot design through a relational lens (Lupetti et al., 2019) rather than treating robots as independent technological entities.

10.4.4 Extensibility - How can the process and outcomes be extended or built upon by others?

This doctoral thesis informs future work in the field of HRI by introducing casual collaboration with bystanders as a new way not only to ensure the operation of urban robots, but also to foster more positive and sustainable human–robot relationships. The knowledge synthesised from this work serves as a valuable reference for future efforts aimed at creating the smooth integration of cyber–physical systems into urban spaces, by (1) embedding the perspective of mutual dependency into the design and development process, and (2) building directly on the design concepts and implications generated in this research to inform future approaches for casual human-robot collaboration. Furthermore, as the participants in this thesis were primarily younger adults with full mobility, future research can extend this work by examining how casual collaboration may be experienced across more diverse publics, such as older adults and people with diverse mobility or access needs.

10.5 The Way Ahead

Looking ahead after this thesis, I see four directions for future work.

First, while this research focused on the interaction design aspect of casual collaboration between bystanders and urban robots, such collaboration exists within a broader socio-technical ecosystem. It is therefore worth examining how these everyday encounters fit into the wider network that involves more diverse stakeholders, including robot service providers, system operators, and service recipients. Understanding how casual collaboration contributes to or is shaped by this larger ecosystem could help ground the design implications of this work more firmly in real-world practice.

Second, the concepts developed in this research were evaluated in controlled lab settings and through a short-term in-the-wild deployment. In such contexts, the novelty of the interactions may have influenced people's reactions and assessments. This is particularly relevant for concepts that involve playfulness, where the initial excitement and curiosity could shift over time. Therefore, it would be valuable to conduct long-term deployments to examine how people's engagement, interpretation, and attitudes toward casual collaboration with urban robots evolve with prolonged exposure. Such studies could provide deeper insight into the sustainability of casual collaboration in public life and how playful ways of engaging bystanders mature within everyday urban environments. These insights would, in turn, help refine designs that can be sustained over long-term deployments and carry enhanced pragmatic value.

Third, this investigation focuses on one specific type of cyber–physical system—urban robots. However, there is an increasing number of other intelligent systems embedded in urban environments, such as smart public infrastructures that include adaptive traffic lights, sensor-based environmental monitoring systems, and AI-powered public service booths. I see many similarities between these systems and urban robots, as both are intelligent technologies designed to provide services in public spaces while operating under contextual and technical limitations. Thus, it is worth investigating how human collaboration may play a role in supporting their functioning, and how insights from this research could be transferred to inform the design of other urban technologies.

Fourth, playfulness emerged as a recurring design theme across multiple projects in this thesis, yet it was not examined as a central focus in its own right. Rather than treating playfulness in the conventional sense of entertainment or amusement, as has often been the case in previous urban robot research (Hoggenmueller et al., 2020b; Lee and Jung, 2020), this thesis positioned playfulness as a way to invite attention and support specific interactional purposes. This opens up new design opportunities to reconsider the role that playfulness can play in public human–robot interaction, and invites future research to examine more systematically how playful design strategies may operate in such contexts.

Finally, through the process of running the empirical studies, I discovered a lack of quantitative measures tailored to casual human–technology encounters in public spaces. Existing questionnaires predominantly originate from human–computer interaction contexts that assume a clear user–system relationship, focusing on constructs such as user experience, perceived usability, or other forms of evaluation grounded in purposeful use. These instruments are not well suited to bystander encounters, where interactions are unplanned, momentary, and shaped by situational and social dynamics rather than deliberate engagement. Developing quantitative measures that capture constructs specific to casual encounters would be useful for advancing empirical research on human–technology interactions in unstructured public settings.

10.6 Conclusion

This thesis set out to investigate how casual collaboration between urban robots and bystanders unfolds in public spaces, and how interaction design can support such encounters. Drawing on contextual insights developed through online ethnography and design probes, design understandings from design workshops and concepts evaluations, and empirical findings from controlled lab studies and in-the-wild deployments, the research traced how these encounters emerge, how they can be mediated, and how they are made sense of by people.

Taken together, these insights articulate a cohesive framework for understanding casual human–robot collaboration in urban settings. First, everyday spatial conflicts show how casual collaboration can be understood as the balancing of human–robot spatial rights, revealing how social expectations and design interventions can together shape moment-to-moment negotiation in shared spaces. Second, the otherness of robots in human-centred urban infrastructures highlight how collaboration emerges when people help bridge robot–environment misalignments, with design interventions repositioning humans not as external helpers but as co-present actors within a shared urban ecology. Third, moments of robotic uncertainty reveal opportunities for machine autonomy to become relational and distributed across street-level ecology, with design interventions helping to overcome the physical, perceptual, and psychological distances introduced by bystanders' positions in relation to robots.

In conclusion, this thesis adopts a relational perspective on urban robots and the bystanders who encounter them, arguing that casual human–robot collaboration is an essential foundation for their smooth integration into public life. Rather than treating these encounters as disruptions or breakdowns, designers and researchers should recognise them as moments of interdependence through which human–robot relations are continuously made and refined. Designing with this interdependence in mind invites us to envision urban futures in which living with robots is not simply a matter of spatial co-presence, but a more mutually supportive and symbiotic form of coexistence.

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