Understanding Interactions for Smart Wheelchair Navigation in Crowds

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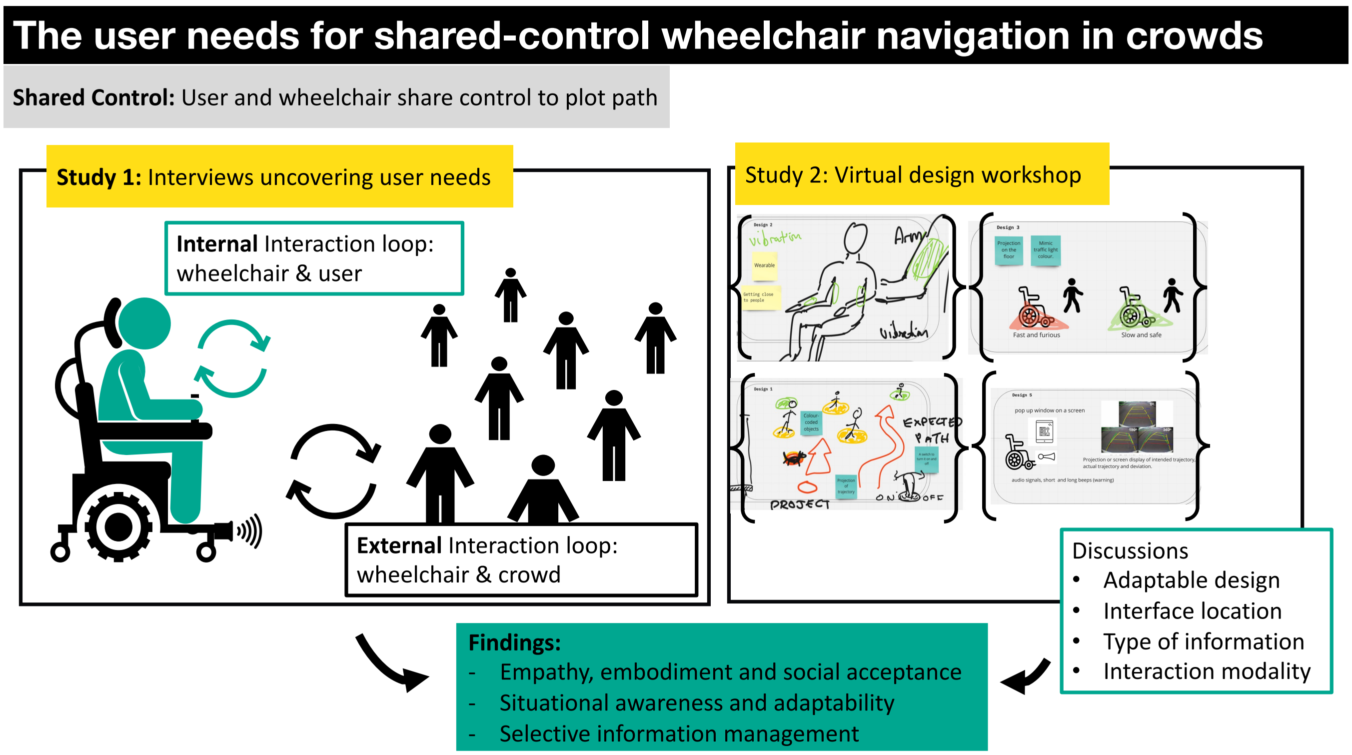

Figure 1: A visual abstract for this paper. We conducted two studies including a series of semi-structured interviews and a co-design workshop to understand user needs for shared control wheelchair navigation in crowds.

ABSTRACT

Shared control wheelchairs can help users to navigate through crowds by enabling the person to drive the wheelchair while receiving support in avoiding pedestrians. To date, research into shared control has largely overlooked the perspectives of wheelchair users. In this paper, we present two studies that aim to address this gap. The first study involved a series of semi-structured interviews with wheelchair users which highlighted the presence of two different interaction loops, one between the user and the wheelchair and a second one between the user and the crowd. In the second study we engaged with wheelchair users and designers to co-design appropriate feedback loops for future shared control interaction interfaces.

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Based on the results of the co-design session, we present design implications for shared control wheelchair around the need for empathy, embodiment and social awareness; situational awareness and adaptability; and selective information management.

KEYWORDS

Smart wheelchairs; Shared control; Wheelchair-pedestrian interactions; Wheelchair-user interactions; Navigation in crowds

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1 INTRODUCTION

Power wheelchairs represent an essential tool for many people with disabilities, enabling them to extend their mobility, carry out basic activities and participate fully in society [72]. However, environmental barriers such as narrow doors and busy streets can hinder the mobility of power wheelchair users, especially when an individual struggles to perform fine movements necessary for navigating spaces with many obstacles [37, 40, 80]. To this end, researchers have been developing smart shared control wheelchairs, which are normally built on standard power wheelchairs with additional modules for perception, navigation, or interaction purposes [79]. Shared control is a semi-autonomous interaction mode that sees the user and the smart planner control the final motion of the wheelchair collaboratively. The user establishes the direction of the movement while the automated system takes care of avoiding collisions [55, 79]. Compared to a fully-autonomous mode of interaction, shared control maintains the agency of the user [84].

Shared control for power wheelchairs has been researched for over two decades [79]. However, most studies have focused on establishing the feasibility of the technology in static or simple dynamic environments, which lack the complexity associated with the real-life situations faced by many wheelchair users [19, 36, 55, 82]. Recent advances in object tracking and trajectory prediction allow the application scenarios to be extended to crowds [29, 51, 83], bringing the technology closer to being deployed in the wild. However, the role of users is still widely overlooked in research. The only previous study we found, which specifically looked at the shared control wheelchair users driving through crowds in urban environments identified two dynamic loops constantly interacting as the person navigates through the crowd [98]. The first loop takes places between the user and the wheelchair (internal), whereas the second loop takes place between the user-wheelchair group with the crowd (external) [98].

In recent years, HCI researchers have explored user perspectives on different wheelchair interaction modalities in a variety of contexts and applications [22, 24, 62]. Moreover, studies have also looked at how wheelchair users interact with pedestrians and other elements of the urban environment, particularly focusing on the accessibility challenges that many of these interactions can generate [3, 14, 44]. However, these two interaction loops are rarely explored in combination. Such exploration is essential to understand the user requirements for a shared control power wheelchair which would allow for ease of navigation in crowds.

The present study answers an important research question that is essential to any successful deployment of shared control wheelchairs in the real-world: **What do power wheelchair users need to be able to use a shared control wheelchair in a crowded environment, and how can we design new interactive systems that ensure safe and empowering navigation experiences?** To address this question we conducted two studies. The first study explored the user experience and difficulty associated with driving through crowds, examining the requirements for a shared control system from a user perspective through a series of semi-structured interviews. In the second study, we conducted a design workshop with wheelchair users and designers to develop ideas for different interactions interfaces that could support shared control wheelchair navigation across a variety of crowded scenarios. Both studies highlighted the need to build two-way interaction systems for increasing pedestrians' situational awareness as much as facilitating user navigation, and identified the needs of adaptable design which could adjust to various situations. Based on these results, we extract broader design implications for interaction systems supporting wheelchairs navigation in crowded environments.

The contributions of this paper include: 1. An understanding of requirements and challenges for smart wheelchair use in crowds. 2. The conceptualization of an interaction interface for smart wheelchairs which helps to manage interactions between user, wheelchair, and pedestrians across different crowd scenarios. 3. Reflections on the implications of findings highlighting the need to create empathetic communication between wheelchairs and other pedestrians, promote situational awareness to ensure adaptability and managing information overload during navigation in crowded environments.

2 RELATED WORK

The work presented in this paper builds on three areas of research: smart wheelchairs and shared control, user-wheelchair interactions, and interactions between wheelchairs and autonomous vehicles with crowds.

2.1 Smart wheelchairs and shared control

Smart wheelchairs are fully or partially autonomous devices which can provide driving assistance to the user by planning and following a collision free path [78]. Based on the level of autonomy, smart wheelchairs can be divided into two categories: fully-autonomous [51, 67] and semi-autonomous [19, 36]. Fully-autonomous wheelchairs are effective in achieving high-level goals for indoor and outdoor navigation [43, 67]. Users only need to indicate their preferred destination, and the path planner will then plan and execute the movement of the wheelchair to the intended destination without collision. However, this type of operating mode ignores users' capabilities and their short-term intentions. Viswanathan et al. (2016) explored the level of control desired by the target population of the intelligent powered wheelchair and showed that users prefer to be in control during the operation and/or high level decision-making [88], this coincides with the findings from the study of Biddiss et al. (2007) which indicated a strong preference from upper limb prosthetic users to retain as much control as possible when using their prosthetic devices, and to not have a fully robotic arm which took over control of their intended movements [16]. Semi-autonomous wheelchair control builds on this sentiment, and could potentially be appreciated by more users due to its collaborative characteristics.

The core of a semi-autonomous wheelchair lies in its control sharing strategy. A hierarchical shared control framework allows the user to remain in charge of high-level tasks such as choosing a desired manoeuvre upfront and then have the wheelchair take control of the low-level tasks necessary to avoid collisions [35, 82]. A second kind of shared control is achieved by continuously blending the input from both the user and the motion planner [19, 36, 55]. This mode can be thought of as riding a horse, where the horse executes the final motion based on the collaborative effort between itself and the rider [42]. For this type of shared control strategy, the wheelchair will not move unless input commands from both parties are received. This characteristic allows the user to retain greater control authority and allows more collaboration between the user and the wheelchair. Both control sharing strategies do not require perfect user input which makes them suitable for assisting users with limited upper limb dexterity who might struggle with the traditional joystick interface, and potentially all power wheelchair users who need to negotiate challenging scenarios.

Navigating through a crowd has been previously identified as one of the most difficult scenarios for wheelchair users [90]. It represents a potentially ideal application for shared control wheelchairs as it requires fine movement control that can be extremely challenging for many users. Although still computationally complex, recent advances in people tracking and trajectory prediction have boosted the research supporting the seamless navigation of robots through crowds [29, 57, 83]. However, despite some similarities concerning the placement of sensors and the use of algorithms governing obstacle avoidance, a shared control wheelchair involves a human user in the control loop rather than an autonomous system, which introduces specific requirements for user-wheelchair interaction. In addition, driving such a wheelchair in crowds introduces an additional interaction layer between the user-wheelchair unit and the surrounding pedestrians [98]. The next two sections give a description of these two interaction channels and the past work that has been done in these areas.

2.2 User-wheelchair Interactions

Interaction between users and wheelchairs have been actively explored in the HCI community [2, 9, 21, 23, 24, 39, 46, 62, 90]. Much of the research on power wheelchair use both within and beyond HCI has focused on how users operate different input device ranges from commercial ones such as joystick, head-array, sip-puff to research prototypes of user-centred control systems [2, 21, 23, 39]. On the other hand, fewer studies have looked at how these different control systems can feed information back from the wheelchair to the user with the aim to support navigation [24, 46, 90]. Such clear and effective feedback mechanisms between the user and the power wheelchair are essential to the success of a shared control system.

When using a smart wheelchair, the user indicates their intention to move in one direction through an interface, using either a traditional joystick or another type of input device. However, due to the dynamic and collaborative nature of the control loop, the final motion of the wheelchair may not fully match the user's expectation, which can cause frustration due to the mismatch between the actual wheelchair behavior and the one anticipated by the user [20]. This has led to an explainable shared control paradigm which looks to resolve this misalignment while assistance and information feedback are considered together [100], as frustration can be reduced with better communication channels from the wheelchair to the user [89]. As a consequence, researchers have looked at different ways of providing feedback to the user about the systems' decisions, thus helping them build a mental model of the navigation assistance [90, 101].

Feedback can be provided via the same interface used to provide the initial driving instruction or through a different one. Researchers explored feedback techniques through different modalities, among which haptic feedback has received the most attention. Wang et al. (2011) tested force feedback via a haptic joystick which blocked the wheelchair movement in the user's chosen direction if the system believed such action would lead to a collision [91]. Hadj-Abdelkader et al. (2012) and Morere et al. (2015) used active and passive force feedback, simulating a spring effect as the user moved towards an obstacle [46, 63]. Both of these examples used the same channels for feedback, however this feedback can interfere with the driving action, particularly when there is a mismatch between the driving commands of the user and the collision avoidance system of the wheelchair. To address this concern, researches have explored providing haptic feedback through wearable devices which are disconnected from the input mechanism used for driving. Devigne et al. (2020) used wearable vibrotactile feedback to inform the wheelchair users about the direction of the obstacles, two studies involving a small number of participants have demonstrated the viability and effectiveness of the proposed technique comparing it to not providing any environmental cue [32]. Visual feedback has also been explored and added to the joystick, however, possibly due to the simplistic experimental set-up people chose not to look at the lights and the authors suggested that visual feedback should be provided in a more intuitive way than being attached to the joystick[91].

Carrington et al. [25] (2014) explored user preference for input and output interface for a power wheelchair, and proposed form factor possibilities for chairable and wearable devices. When examining possibilities for output modalities for visual feedback, participants showed the strongest preference towards the use of head-mounted based output, compared to add-on screens and environmental projections which were seen as less practical across different situations. Recently, augmented reality (AR) has also been used for assisting smart wheelchair navigation. Through the examination of various augmented cues, Zolotas et al. (2018) and (2019) demonstrated the potential for using AR as a feedback channel between the wheelchair and the user. However, the authors highlighted that care should be taken in the presentation of information to ensure that users are provided only with significant information that helps driving without creating unnecessary distractions [100, 101]. Finally, multi-modal interfaces to provide feedback for shared control of power wheelchairs have received increasing attention. Studies showed evidence that declines in single sensory channel processing capability due to aging can be potentially compensated by multisensory inputs [53]. Kumar et al. (2017) proposed that feedback could be provided in a more intuitive way through the combination of a user-centric wearable skin stretch device and a haptic joystick [52]. A combination of haptic, visual and auditory feedback was proposed for older adults and successfully tested by [91]. However, all these feedback methods for shared control wheelchair driving were tested and evaluated in simple indoor environments, and whether such feedback would work in crowds remains unclear. In addition, most work focused on the usability test and involve wheelchair users only during the testing stage where the user has limited opportunity to express their desire for the design of the feedback information and modality.

2.3 Wheelchairs and Autonomous Vehicles Interactions with Crowds

Recently, the HCI community has begun to explore the interactions between autonomous vehicles and various groups of road users, including wheelchair users [4, 49]. Other studies have also looked at the interactions between wheelchair users and other road users both on the sidewalk but also on public transport, examining conflicts and accessibility issues that can arise as a result of these interactions[81, 86]. However, to our knowledge, no study has investigated how these interactions could change when the wheelchair becomes a semi-autonomous vehicle and what would be the consequence on user requirements for smart wheelchairs. Interactions between autonomous vehicles (or other robots) and other pedestrians (including wheelchair users) are normally moderated by external Human Machine Interfaces (eHMIs). These are interfaces installed on, or projecting from, the external surface of a vehicle that provide information about the vehicle's status or give suggestions to the other road users [13]. Based on the modality, eHMIs can be classified as physical, auditory, or visual. Mahadevan et al. (2018) studied the three modalities (visual, audio, physical) and found that visual was the most preferred. While there is potential for audio and physical feedback, some participants found them difficult to be perceived and processed in real world scenarios. Being the most extensively investigated modality [31, 61], state-of-the-art research has explored different ways of visual communication including "light strips" [38], "laser projections" [33] and "display" [69], exploring how they can be used to convey different information including "vehicle's states" and "suggested actions for the pedestrian" [71]. While studies indicated that communicating via an eHMI increases the pedestrians' perceived safety and the level of comfort [27, 45], it is not clear which information should be prioritized.

Although the literature exploring the interaction between pedestrians and autonomous vehicles is extensive [17, 26–28, 30, 45], only a limited number of studies investigated interactions between a wheelchair and the surrounding people. Watanabe et al. (2015) conducted an experiment to explore how the communication of movement intention from a power wheelchair, through a projected light path on the floor, affected the interaction between the wheelchair and a pedestrian at a road crossing. Results indicated that pedestrians preferred to be made aware of the wheelchair's navigational intention which resulted in smoother movements compared to the no communication scenario [92]. Similarly, Moondeep et al. (2018) used a red projected arrow to show the wheelchair's future direction to surrounding pedestrians and the results from their studies show that such methods are also successful in increasing cooperation from the participants [77].

Despite the potential of eHMIs in building interactions, [71] pointed out that many design challenges such as the medium, the color, and the location of the eHMIs still need to be further explored. In relation to smart wheelchairs, the fact that the user can be seen by pedestrians may further affect the design requirements of the communication tool. Moreover, all these studies only explored the perception of surrounding pedestrians interacting with a smart wheelchair, but it is not known what the needs and preferences of wheelchair users driving the smart wheelchair through a crowd might be. In this paper, we explore for the first time the user needs for shared control wheelchair driving in crowded environment by considering both the user-wheelchair interaction and the wheelchair (user)-crowds interaction loop. These needs bring us one step closer to in the wild testing of shared control wheelchairs.

3 STUDY 1:NEEDS AND EXPERIENCES OF DRIVING WHEELCHAIRS THROUGH CROWDS

While previous work [88] has explored the needs and control preference for older adults with cognitive impairments, in this study we extend the scope to understand general power wheelchair users' driving experience in crowds, identify the user needs and design requirements for smart wheelchair use.

3.1 Methods

To gather insights from the previous experiences of power wheelchair users about the challenges encountered when maneuvering their wheelchairs through a crowded environment and extract potential requirements for how a smart shared control wheelchair should behave, we conducted a series of semi-structured interviews with power wheelchair users.

3.1.1 Participants. Participants were recruited through a combination of social media advertising, mailing lists of local organizations of people with disabilities and targeted emails to an existing repository of potential participants collected by the research group. Participants who responded positively to the ad were quickly screened to confirm that they were above the age of 18, able to provide informed consent, and that they used a power wheelchair regularly as a means of mobility. Participants who met the inclusion criteria and gave their consent for participation were invited to take part in the interview study. A total of 15 power wheelchair users were recruited for this study. Individual one-to-one semi-structured interviews were conducted with 12 participants from UK, whereas 3 participants (from UK, France and Switzerland) were interviewed as a group. The group interview was carried out in this format for convenience reason as all three participant had joined an online open event linked to the project. The group interview may elicit richer understanding of the participants' experience comparing to the one-to-one interview. Table 1 provides a summary of participants characteristics.

3.1.2 Materials. As one-to-one interviews took place before the start of the global pandemic, they were conducted in person in one of our university building, and were recorded with a portable audio recorder. The group interview was instead conducted remotely as it took place after the start of the pandemic. For the remote group interview, we chose to use the videoconferencing platform MS Teams as it complies with data protection regulations and university ethics standard.

3.1.3 Study Procedures. For both one-to-one and group interviews, we developed a semi-structured interview guide through an iterative process that involved all members of the research team. The questions started by asking participants about their experience in driving through crowds, what they found it difficult and how they managed, difficulties across different scenarios. Participants were then shown an image of our intelligent wheelchair prototype (see Figure 2) together with a short explanatory video demonstrating a simulated wheelchair navigating in a crowded street. Participants were then asked about their opinions of smart shared control wheelchairs, including detailed questions related to specific features and potential challenges in various crowd scenarios. Individual interviews lasted between 30 and 45 minutes, whereas the group interview lasted for approximately 1 hour.

3.1.4 Data Analysis. The collected data included audio recordings from one-to-one and group interviews. Audio recordings were transcribed verbatim by the first author. Thematic analysis [18] focusing on semantic interpretation of the data was used to conceptualize themes from the interviews and following an inductive open coding approach. Initial coding was carried out by the first author and, as the analysis progressed, the conceptualization of themes was discussed across the members of the research group.

3.2 Results

As a result of our analysis, we conceptualize three themes that help to frame the experience of power wheelchair users and understand the requirements for shared control wheelchairs suitable for crowd navigation: "Communication", "Balancing safety, autonomy and social aspects" and "Ethics".

3.2.1 Communication. Interestingly, although most wheelchair users identified crowds as one of the most difficult scenarios to navigate, where frequent collisions happened, they thought that the problem was largely associated with pedestrians' lack of awareness and understanding of power wheelchairs, rather than the control of the wheelchair itself. Overall, participants felt ignored by other pedestrians, which could lead to challenging navigation and accidental collisions.

"If you are in a wheelchair, you become invisible and people just don't see you. . . ."(P1)

"Especially in places such as airports and train stations, people may not see you, and they will fall on you." (P3)

Some participants stated that they had to use extremely direct strategies in order to deal with distracted pedestrians and safeguard themselves.

"I normally shout at people or use my elbow to avoid them fall on me."(P1)

"Sometimes I can ask a person to volunteer to clear the way when I'm coming, or I can make a sound like..'zzzz' , so people will turn their head back and see me coming." (P8)

These insights help us identify the need for building interaction systems that facilitate communication between wheelchair users and the surrounding pedestrians to promote safety and minimize frustrations. It was pointed out by some wheelchair users that the most natural and effective way of increasing pedestrians' awareness of the wheelchair is by increasing the seat height, so that the wheelchair user can be at pedestrians' eye level. However, participants also stated that this could not be a permanent solution as it could hinder stability and convenience of transport. When asked about adding extra audio/visual system to the wheelchair to alert the surrounding pedestrians and communicate the intended direction of movement, most interviewees thought that these features could be helpful, but they should be effective and unobtrusive. In addition, many participants pointed out that the design should be adaptable to different crowd scenarios. Moreover, these systems should help to communicate the movement of the wheelchair without drawing attention to a users' disability:

"It can make people better aware [that] the wheelchair is coming, but I don't want to draw extra attention on me, especially on my disability.."(P6).

Communication was seen as a priority not only between the wheelchair users and other pedestrians, but also between the user and the smart power wheelchair. Participants often found that power wheelchairs did not provide any feedback about the surrounding environment, which could be helpful when navigating crowded environments. People commented on a lack of natural feedback from a power wheelchair, when compared to a manual wheelchair:

"You don't have tactile feedback in these wheelchairs, whereas if you were in a manual chair, You know, you can feel the resistance when you're trying to push it."(P2).

More generally, feedback was seen as beneficial when using a smart wheelchair, as sensors might detect unseen obstacles that could variate the expected trajectory of movement and appropriate feedback could help to avoid confusion and frustration.

"Yes, I would like to receive this kind of thing [i.e. feedback from the wheelchair], it would be nice to be told what it is going to do, so that you would be aware, and you're not taken by surprise."(P5).

3.2.2 Balancing safety, autonomy and social aspects. For many users, one of the most attractive features of a smart wheelchair was the increased safety brought by different sensors that could be leveraged to successfully navigate crowded environments and avoid collisions with objects or people. Shared control options were also seen as a way to make power wheelchairs more accessible to users who would struggle to use conventional interfaces effectively. This additional level of safety and autonomy brought levels of excitement from some people:

"It is a superb design! Clearly, it would enable more people to drive, because it's not excluding you on the basis of an inability to drive." (P8)

ID	Age	Self-identified Gender	Years of Experience as wheelchair user
P1	63	Male	47 years
P2	26	Female	20 years
P3	40	Male	22 years
P4	25	Male	15 years
P5	65	Female	36 years
P6	47	Female	27 years
P7	46	Male	32 years
P8	47	Male	>30 years
P9	44	Male	26 years
P10	28	Male	12 years
P11	62	Male	8 years
P12	38	Female	27 years
P13	76	Male	9 years
P14	32	Male	18 years
P15	55	Male	30 years

Table 1: Demographic data of wheelchair users who took part in Study 1. Note the years of experience combines the manual and power wheelchair use.

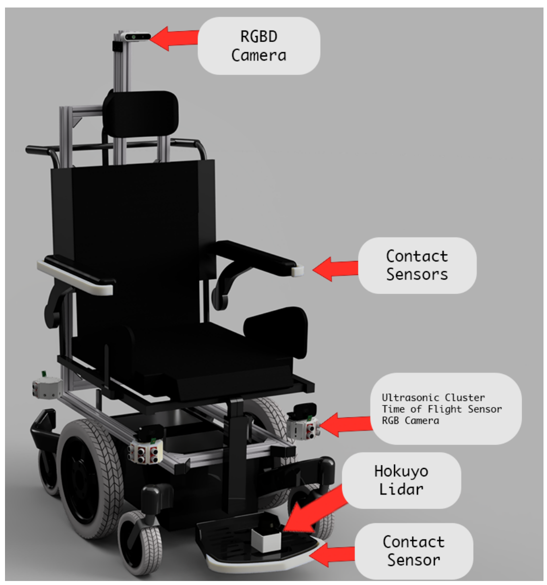


Figure 2: An image of our smart wheelchair prototype

However, other users expressed concerns about the fact that functions for obstacle avoidance could override their decisions and suggested that the balance between smart wheelchair sensors and user command should be based on the scenario and the user's capability. For example, at a shopping mall or a social gathering obstacle avoidance could be useful to help users navigate, as many pedestrians could be moving around the space in unexpected ways. On the other hand, in an office space that the user is familiar with, the same feature could become an annoyance as it might interfere with the user intention to approach a desk or a photocopy machine.

Users thought that the need for safety should be balanced with the need for autonomy. Participants unanimously rejected the idea of a fully autonomous wheelchair that P4 argued "*would make me feel like cargo*". Several participants suggested that the system should have some form of context awareness and adapt the amount of assistance based on the context, for example reducing user autonomy and increasing smart control when one is tired. Participants with more experience driving power wheelchair were clear that the assistance from the system should not override their decisions or significantly impact their driving.

"I'm pretty good at driving the wheelchair and perceive the available space...If I say go through that gap, the technology should be making sure that I'm going through that gap and doing the avoidance, but not slowing down to crawl." (P10)

Social situations were the only ones in which participants felt that allowing the smart wheelchair to take complete control of the driving might make sense, as it would allow them to focus completely on interacting with the people around them.

"Full autonomy will allow me to focus on other things. For example, say take me to platform H, it will take me automatically there while I can focus on chatting with my friend." (P11)

3.2.3 Ethics. The need to strike a balance between ensuring the safety of surrounding pedestrians and preserving the user autonomy also led to some interesting reflections amongst participants about negotiating shared control from an ethical point of view. This was felt to be particularly crucial when there is conflict between the needs and commands of the user and the safety system of the wheelchair, as participants felt there were different considerations to be taken into account. For example, P5 highlighted how, making sure that the wheelchair could safely move and avoid collision through a crowd, could not be achieved by constantly changing the trajectory of movement as this could lead to discomfort for users themselves.

"In the crowds, it is most likely the wheelchair will keep changing its direction to avoid people, which is the least thing I would want to have..It can be confusing and uncomfortable.." (P5)

Again, contextual awareness was seen as crucial as in certain environments, such as hospitals, the system should prioritize avoiding any type of collision over ensuring users comfort as "*people there may be vulnerable and it is important not to hit them*" (P1). Participants also highlighted that, when it came to preventing collisions, there might be a need to negotiate conflicting priorities. Rather than leaving the decision to the smart wheelchair, they felt that the user would be better placed to make that decision.

"Sometimes the system don't realize that you have perceived an issue and they will do something that you think is irresponsible..For example, you could have a collision avoidance system that is doing the best to avoid you running into a wall, but actually you are trying to get closer to the wall because you are trying to avoid a child running on the pavement" (P11)

Finally, participants stated that having their decision overridden by a shared control system might create misunderstandings with other pedestrians, in particular when the wheelchair movement might cause an accident or a near miss. The fear here was that the intention of the driving would be interpreted as the sole responsibility of the user.

"When the wheelchair does something out of my intention and that causes unhappiness for other people, I don't want people to think it is what I intend to do and I'm a bad guy." (P15)

4 STUDY 2: DESIGNING COMMUNICATION INTERFACES FOR SMART WHEELCHAIRS

By examining users' point of view in study 1, we highlighted the need for smart wheelchairs to have a clear and effective "internal" and "external" communication system to:

1) Facilitate users' creation of reliable mental model about the wheelchair intended behavior.

2) Provide information about the level of assistance provided (and allow users to adjust it if needed).

3) Increase pedestrians' awareness of the wheelchair.

To further explore these aspects and identify potential solutions for successful user-wheelchair-pedestrian interaction systems, we conducted a second design-focused study.

4.1 Methods

Our second study was a virtual design workshop that involved both wheelchair users and designers. The aim of the design workshop was to explore and understand how internal and external communications systems for smart wheelchairs should be developed to support seamless navigation through crowds.

4.1.1 Participants. Power wheelchair users in the design workshop were recruited using a similar strategy to the one described for Study 1 using a combination of social media advertising, mailing lists and targeted emails. Inclusion criteria were the same as those for Study 1. Designers taking part in the workshop were recruited from our extended research group as they would have some experience working with people with disabilities, but had to have no previous involvement with the project to avoid bias.

Eight participants (6 adult power wheelchair users and 2 designers) took part in the design workshop. Table 2 provides a summary of participants characteristics.

4.1.2 Materials. The workshop was conducted remotely through the online video conferencing tool MS Teams. In addition to being a viable data collection tool, studies show that remote engagement allows individuals to respond to design prompts in a convenient manner[59, 60]. To elicit engagement from the participants and manage collaboration, we used an online Miro board as design space. This tool works as a collaborative canvas and allows participants to easily demonstrate their ideas by writing, drawing or simply dragging and dropping existing design icons on a shared space. Due to the concern that wheelchair users without previous experience using these kinds of collaborative tools might encounter difficulties throughout the design workshop, two additional researchers were available throughout the virtual workshop to support power wheelchair users and help them manage the board and input their ideas on the shared canvas if needed. The workshop was audio and video recorded according to participants' consent.

4.1.3 Study Procedures. At the start of the workshop, participants were given an introduction of the project and shown a video explaining what a smart wheelchair is and how the use of a shared control system might support navigation but also affect the driving experience. From our learning during Study 1, we noticed that wheelchair users with varying expertise and characteristics might have significantly different requirements that are hard to address in a single design session. To overcome this, and facilitate brainstorming amongst participants, in this study we used a persona based method and introduced an imaginary character "Ann" to our participants. Ann was described as a woman of 60 years who has difficulty using a standard power wheelchair due to severe arthritis. In order to not limit the exploration of different interaction modalities, we designed Ann to have unimpaired visual, hearing and cognitive capability. During the workshop, we asked participants to design the communication system for Ann's smart wheelchair which would allow her to navigate in two crowded scenarios: crossing a busy

ID	Self-identified Gender	Age	Years of experience of using power wheelchairs
P1	Female	65	14
P2	Male	36	6
P3	Male	40	10
P4	Male	20	2
P5	Male	25	4
P6	Male	60	18
ID	Gender	Age	Years of experience as a designer
P7	Male	50	25
P8	Male	29	10

Table 2: Demographic data of participants for Study 2

street and reaching a help desk in a crowded hospital. These scenarios were chosen for two reasons: firstly, these are typical use cases for a wheelchair navigation in crowds; secondly, these scenarios have inherent differences and may require the communication to be designed differently.

After the introduction, participants were assigned to two breakout rooms, each featuring 1 facilitator (researcher) and 1 designer. Due to one wheelchair user's network issues, 2 wheelchair users were assigned to room 1 whereas room 2 featured 4 wheelchair users. Each room was presented with a different scenario of smart wheelchair crowd navigation. The facilitator shared the screen with the Miro board. Participants in each breakout room were asked to complete three activities. Firstly, they had to identify the key components that characterize interactions and communication during navigation in their particular scenario, and formulate ideas about how the interaction system should work. The prompts for brainstorming included "What information should Ann receive?", "What information should the pedestrians receive?", "How should the information be presented?", "When should that be presented?". While wheelchair users spoke about their ideas, the facilitator helped to manage the Miro board asking them to confirm that the correct details were being captured at all time.

Secondly, participants were presented with a series of ideas for interaction systems that had been proposed in related literature. Participants were asked to give their opinions on whether the information provided and the modality of the interaction would be useful for Ann and surrounding pedestrians in each scenario. Finally, wheelchair users and designers were asked to work together on visualizing their ideas developing diagrams specifying important design parameters which included "function of the interface", "location of the interfaces", "timing of communication", "cues provided" and "interaction modalities". A collection of icons were provided in the Miro board to facilitate the design session, but participants were told that they could design new icons if needed. In the end, all participants were asked to rejoin the main room and each group presented their designs and ideas to the other, which was followed by a short discussion. The duration of the design workshop was 2 hours.

4.1.4 Data Analysis. All the ideas and designs proposed by participants in the Miro boards were collected, together with the audio/video recording from the design workshop. Audio recording were transcribed. Thematic analysis [18] was carried out primarily by the first author with the aim of identifying and defining the features for smart wheelchair interfaces. We used a hybrid approach [41] by deductively establishing broad categories for "Type of information needed", "Location of the interface" and "Modality of the interaction", while allowing for any additional theme and sub-theme directly from the data using inductive coding.

4.2 Results

Four themes were conceptualized from our analysis of the design workshop. Beyond the three themes we deductively established "Type of information needed", "Location of the interface" and "Modality of the interaction", a fourth one named "Adaptable design" is described. A high level summary of the design workshop output is listed in Table 3.

4.2.1 Type of Information Needed. Through the categorization and analysis of the information necessary during shared control wheelchair navigation in crowds, it clearly emerged that the participant considered both internal and external communication to be equally important. As a person drives their shared control wheelchair through a crowd, participants stated that the user should receive environment information about what the wheelchair has perceived (e.g. what obstacles have been detected and what are their characteristics), what the wheelchair has decided (e.g. what is the smart wheelchair's final decision on its motion and future trajectory), as well as the alignment or deviation between the user and the wheelchair.

I want to know where those pedestrians are, their movement, and especially for those that are behind me.(P5) *"The system should tell me if the wheelchair is going to accelerate, and which way it is going."* (P4)

In addition, participants identified the need for the wheelchair to externally communicate with the surrounding pedestrians. In this regard, the smart wheelchair and the user were seen as a combined unit which needs to communicate its final decisions and future movements to the surrounding people.

Pedestrians should know if Ann is approaching [...] Knowing the future trajectory of the wheelchair would help. (P3)

	External	Internal		
Timing	Close to the pedestrians	Moving	Detect objects in its path	Deviates from the user's intention
Type of information	Wheelchair information	Wheelchair information	Environment information	Human-robot alignment
Interaction modality	Visual (primary) Audio (based on the scenario and emergency)	Visual Haptic Audio (based on the scenario and emergency)		
Interface location	On the wheelchair	On the wheelchair armrest – add-on screen arm(wearable), joystick, armrest – haptic feedback		

Table 3: A high level summary of the design workshop (study 2) output

Although the content of the information, the cues used to communicate it, and the timing for communication may be different between information directed to the user and to surrounding pedestrians, participants felt that there was a definite connection between the external and internal communication system of the wheelchair. As P5 pointed out, comprehensive and clear feedback from the wheelchair to the user is essential to build trust in the shared control system and ensure a smooth driving experience. At the same time, if the wheelchair is also able to effectively communicate with pedestrian, making sure that they give way and leave enough space, the amount of feedback to be given to the user will decrease, as the number of "obstacles" around the wheelchair is reduced.

It [Feedback] will help me understand what the wheelchair is doing...so I can trust it [the smart system]. [...] But if people are properly informed, they will just give way to you. (P5)

4.2.2 Interaction Modality. Although participants assigned to different breakout rooms were tasked to design interaction interfaces for different scenarios, we found that most of the features and parameters of systems designed by participants were similar across the two teams. The most substantial differences were related to the desired modality for communicating the cues when crossing a busy street versus when needing to reach a help-desk in a crowded hospital.

Participants designing a smart wheelchair interface system for a street crossing scenario showed a clear preference towards a combined audio and visual feedback system to manage internal and external communication. Their design idea involved a screen on the wheelchair armrest or a wristwatch worn by the user to display wheelchair information. The speed and acceleration profile are communicated to both the user and surrounding pedestrians though color coded projection. A pop-up screen with a voice-over chat-bot could also be used to communicate important messages to the wheelchair user. The choice between the use of audio and/or visual cues would instead depend on the severity of the situation. When the wheelchair is at low risk of hitting people, less obtrusive visual cues are preferred, such a light projected on the ground for alerting pedestrians and a warning on the screen for the user. Audio feedback could also be leveraged in the form of soft and short sounds warning the user that an obstacle has been detected at a certain distance. On the other hand, when the risk of collision between the wheelchair and pedestrians increases, flashing lights and buzzer with longer beeps ware mentioned as a better way to attract the attention of both the user and surrounding pedestrians. Figure 3 shows the diagram created by participants to illustrate their design.

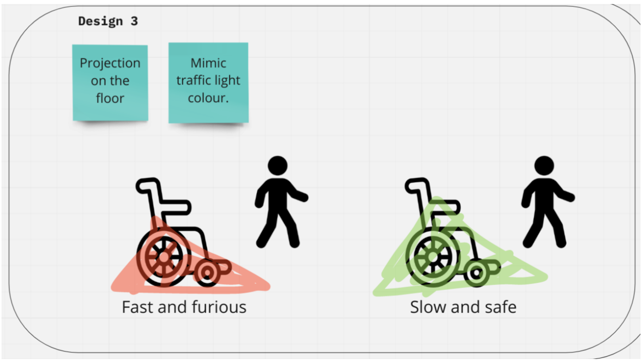
Participants designing a smart wheelchair interface for the crowded hospital scenario showed an inclination towards visual and haptic feedback modalities rather than auditory ones. Their final design idea featured projected light cues such as arrows showing the wheelchair's future trajectory, and circles to highlight detected nearby pedestrians/obstacles. These circles would be color-coded to indicate information about distance (near or far) and type of obstacle (human or object). When obstacles close to the wheelchairs are detected, haptic feedback in the form of vibration from the wheelchair or an armband worn by the user could be provided as a warning. Figure 4 shows the drawing created by a participant to illustrate their design.

In both scenarios, participants found visual communication the most intuitive method to provide feedback to both the user and the surrounding pedestrians. However, participants had no specific preference on how cues should be designed.

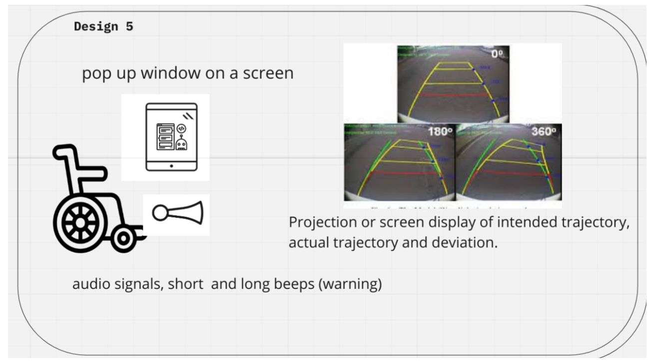
4.2.3 Interface Location. During the workshop, we asked participants to imagine what would be their preferred location for the main interface of the smart wheelchair. Overall, participants expressed a preference for interfaces connected to internal communications systems (i.e. between the wheelchair and the user) to be positioned on the wheelchair itself or to be embedded in a wearable device like a wrist band or a watch that could be worn by the user. However, the choice for the precise location of the interface was largely dependent on the modality of the feedback provided. For visual feedback, an add-on screen on the armrest and projection from the wheelchair were the most popular designs produced by participants. When it came to haptic feedback, some participants felt that this would be better delivered through the joystick, armrest or the back of the wheelchair. On the other hand, 2 wheelchair users (P1 & P3) expressed concerns about a "*chairable*" haptic feedback (see [24] for a reference of the term) and thought that a wearable device on the arm could represent a better solution.

"Haptic feedback can be useful...but I don't want the wheelchair to vibrate...the chair is an extension of my body." (P1)

Interestingly, and in contrast to our expectations based on previously published literature, participants expressed preferences for chairable interfaces also in relation to external communication between the wheelchair and surrounding pedestrians. In particular, both users and designers thought that providing auditory or haptic feedback directly to pedestrians could be perceived as a "*weird*" invasion of one's personal space.

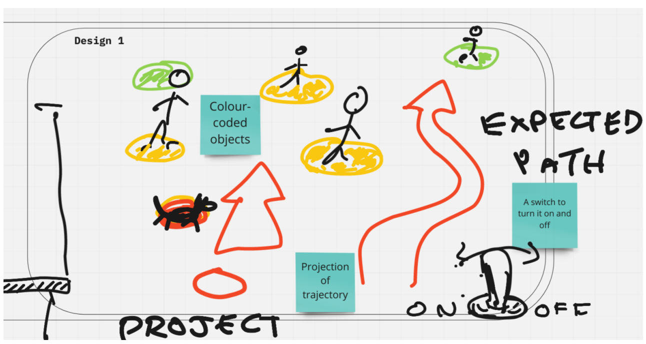


(a) Street Design 1

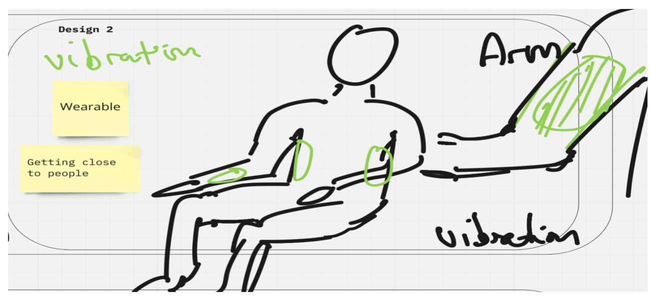


(b) Street Design 2

Figure 3: Two internal and external communication design outputs from the workshop for the crowded street scenario. (a) Traffic color coded projection is used to indicate the wheelchair's speed. (b) The wheelchair's trajectory and its deviation from the user's intention in indicated through "Parking trajectory alike system", either being projected or pop-up in an add-on screen. Short and long audio signals are used for warnings.



(a) Hospital Design 1



(b) Hospital Design 2

Figure 4: Two internal and external communication design outputs from the workshop for the crowded hospital scenario. (a) Expected path and locations of obstacles (color-coded for its property) are projected. A switch is used to turn this function on-off. (b) When the wheelchair is getting close to pedestrians, the user receives warning through wearable haptic feedback.

"Warn the people through their phone is creepy...Imagine it suddenly vibrate or make sound only because that I'm getting closer" (P4)

No specific location preference was discussed by participants in relation to the external visual and audio feedback to surrounding pedestrians (i.e. in which direction should warning sounds be played or at what height should a projected light to indicate direction of movement should be placed) . However all designs produced by participants showed that these outputs were projected directly by the wheelchair rather than connecting to IoT devices used by pedestrians or smart roadside furniture as it had been suggested by previous studies [3, 61].

4.2.4 Adaptable Design. Although wheelchair users stated that receiving comprehensive information from the smart wheelchair was important for them to develop trust in the system and achieve better navigation experience in crowds, they also stated that they did not want the system to communicate with them or other pedestrians at all times. External communication was only desired when the wheelchair was getting close to the pedestrians. On the other hand, when it came to the internal communication between the wheelchair and the user, the information they would want to receive would depend on the specific situation.

All the information are important[...]to prevent a lot of distraction, I think a pop-up window that only shows relevant information is a better idea.(P4)

In general, while the wheelchair is moving, users stated that they would only like to receive general information which are relevant for driving such as acceleration, deceleration, and movement trajectory. A visual display showing the functioning status of the smart wheelchair was also mentioned by participants. However, as the wheelchair detects an obstacle in its path, users would like to receive a haptic or audio warning. Although most participants felt that being provided with additional information (position, number, type) about any perceived obstacle would be helpful, this feature was seen as more desirable when the user is reversing rather than moving forward.

"I only need it [feedback on obstacles' information] when I am reversing...maybe something like SatNav?"(P1)

Finally, while participants found that being informed about the smart wheelchair's planned trajectory is enough in most cases, they expressed a need for more information to understand the reasons for discrepancy when their own instructions are overruled by the shared control system, which might result in the wheelchair motion being different from their own expectation. The idea of a projection or screen displaying something similar to "Parking trajectory system" proposed by our designer (P8) was welcomed by most participants.

Overall, this suggests the need for smart wheelchair interface to have an adaptable design that can respond to the preferences of the user and the constraint of the situation. While the system itself should have the ability to provide appropriate information at suitable time, users should also be allowed to switch the interaction function on-off and choose their desired information.

5 DISCUSSION

Previously, HCI researchers have focused on exploring the interactions between pedestrians, including wheelchair users, and autonomous vehicles [3, 5, 64, 70] and engineering researchers have explored the potential of shared control wheelchairs [20, 36, 55]. Our work represents the first example of research looking specifically at how power wheelchair users would wish to interact with shared control smart wheelchairs, including how they would expect the smart wheelchair to moderate their interactions with other pedestrians when navigating through a crowd.

Our findings across the two studies highlight the presence of design tensions. These need to be addressed if we wish to develop smart wheelchairs that are safe to use when navigating a crowded space, and provide empowering experiences for users, addressing both functional and social needs across different situations.

Navigating a wheelchair through a crowd is acknowledged as a challenging experience due to the presence of numerous moving obstacles [44]. However, rather than manoeuvrability, our participants attributed many of the difficulties associated to navigating through a crowd to the lack of attention from surrounding pedestrians. The observation contribute to our first design tension. The tension we identified was between the need for smart wheelchairs to alert pedestrians of one's presence and ensure that people create sufficient space for passing, and the reluctance of users to attract unwanted attention to themselves and their disability. This finding aligns with much of the literature around social accessibility [54, 75, 76] and the importance of negotiating boundaries between alerting others of one's disability in order to manage expectations and avoid attracting unwanted stares from surrounding people [96].

The need for effectively communicating with surrounding pedestrians without causing excessive disturbances, particularly in environments where participants felt that this would be inappropriate, also emerged from the difference between the two ideas for smart wheelchair interfaces developed during the design workshop. Participants working on the crossroad scenarios preferred interaction modalities that incorporated auditory components, whereas the ones working on the hospital scenario preferred an interface that relied on more discreet visual and haptic feedback. This was not unexpected as hospitals are normally perceived as quieter spaces, whereas a busy street is a more intense scenario which may require a more decisive driving style while at the same time being more easily associated with louder noises. The different preferences towards the use of audio feedback are also consistent with the finding in [50], who reported that people with visual impairments felt more comfortable using an assistive suitcase that emitted audio alerts in public places compared to quieter places such as hospitals and libraries.

Another tension that needs to be negotiated in the design of smart wheelchairs is related to the need to strike a balance between the safety of the system and the autonomy of the user. This is consistent with the findings stated in [88] where the users' attitudes toward intelligent wheelchairs specifically related to user control were explored. Moderating factors in this case were the capabilities of the user, the characteristics of the environment and the specific social situation in which the person is operating the smart wheelchair. As seen in previous studies, the capabilities of the users can be affected by a variety of factors ranging from experience, to tiredness or alcohol use [7, 94]. The more the individual feels that their capabilities are impaired the more they might be happy to let the wheelchair be in charge of navigating through a crowd. Similarly, existing research has shown that when negotiating extremely challenging environments, people with disabilities are not opposed to the idea of receiving help, as long as they can do so in terms that they feel comfortable with [11]. Finally, participants stated that they would be happy to have the smart wheelchair take care of avoiding obstacles in a crowded environment for them, if this would enable them to focus on engaging socially with their companions. This is somehow similar to what is reported by [93], when people with visual impairments stated that, when going around with a sighted companion, they preferred to be guided by them as it enabled them to remain engaged in conversation rather than having to focus on navigational tasks.

A key strategy to better manage both issues of communication with surrounding pedestrians, and the need for balance between safety and user autonomy is to increase trust between humans, both users and surrounding pedestrians, and smart wheelchairs [99]. As explored in some of the recent literature on self-driving vehicles, trust is built when a smart vehicle behaves in a way that matches the mental model of the individual [65]. These mental model are generally based on previous encounters, but also on the level of understanding that the person has of the technology and how it operates [6, 65]. This resonates with literature on technology explainability, both in relation to smart vehicles and other types of complex technologies showing that if a person understands the causality that governs the behaviour of technology (e.g. why a computer vision system does not recognise an object or why a smart vehicle switches lane on a motorway), they are more inclined to trust it and accept mistakes that might occur [73]. From the wheelchair users' point-of-view this aligns with the explainable shared control paradigm [100] and the communication needs expressed in study one, when participants said that they would particularly wish to receive feedback especially when the behaviour of the wheelchair might differ from the original command given. Explainable object-induced action feedback, such as the one proposed by Xu et al. (2020) [97] for autonomous vehicles, where the system flags the specific object detected that leads to a certain action (such as a red light would cause the car to stop), could represent a viable solution to this issue. On the other hand, previous studies on interactions between autonomous vehicles and pedestrians and cyclists needed less specific information, but felt more safe if the eHMI clearly communicated the vehicle awareness of their presence, the intention of the vehicle (e.g. stopping, or turning towards a particular direction) and, in certain situations, the expected behaviour for the participants (e.g. gesturing a pedestrian that is safe for them to cross the road first) [56, 66].

The final tension we want to highlight is the one that emerged between the need to balance the needs of the users with the ones of surrounding pedestrians. In the first interview study, this tension was most visible in the discussions surrounding ethical aspects of smart wheelchairs. All participants agreed that collisions with pedestrians should be avoided at all costs. However, implementing safety mechanisms during crowd navigation could also result in continuous starts and stops that would make the ride uncomfortable and potentially dangerous for the user. In the remote design workshop a similar issue of boundaries between what might be beneficial for smart wheelchair users versus what would be acceptable to the surrounding pedestrians was also touched upon when discussing ideal interaction locations. For instance, users acknowledged that being able to transmit a warning directly to a passerby that was standing in front of them by leveraging IoT connectivity and, for example, making their phone vibrate would be extremely convenient. However, they also felt it would be an unauthorised invasion of other people's personal space. As a result, participants decided that the optimal location of any interaction would also be based on the wheelchair, or easily traceable to it, even if it meant that the feedback provided to pedestrians would be less effective.

The importance of negotiating potentially conflicting priorities when it comes to design interactions for equal access of opportunities has also been highlighted by [14] and [48]. As stated by Bennett et al. (2021), negotiating accessibility between different mobility needs on footpaths, or other crowded spaces, can be extremely challenging [14]. As designers and researchers it is important we make sure to consider how power dynamics between pedestrians, wheelchair users and others can affect decisions we make and how we create accessible or inaccessible interactions.

6 DESIGN IMPLICATIONS

Based on the results from our studies and the reflections on the design tensions we presented in the discussion, we elaborated a series of design implications that we believe would be crucial to the development of future smart wheelchairs.

6.1 Empathy, embodiment and social acceptance

When we compared the proposed internal and external communication design for smart wheelchairs created by participants versus the ones which are more commonly designed for autonomous vehicles, we noticed additional requirements related to the need to include elements of empathy, embodiment and social acceptance in smart wheelchair interaction design. Participants stated that they would consider a smart wheelchair as an extension of their body, akin to what has been previously reported for different types of assistive technology [10, 15]. As such, the way in which the smart wheelchair provides feedback to the user needs to feel appropriate, matching one's expectation for embodiment, which might be different across individuals.

Moreover, when it comes to external communication, the way in which the wheelchair enables interactions between the user and surrounding pedestrians should incorporate considerations around social acceptability and empathetic communication. In contrast with other fully and semi-autonomous vehicles, and in line to what has been reported by users of different assistive technologies, the smart wheelchair is intrinsically connected to the image of the user, becoming part of how people with disabilities perceive themselves and are perceived by others [8, 10, 15, 68]. Hence, any interaction with others becomes a much more personal experience. Although having the smart wheelchair emit loud noise might be an effective strategy to get some careless pedestrian to give way to the wheelchair, some users might feel uncomfortable with such a form of interaction in the same way that they would be reluctant to shout at the top of their lungs for people to move out of their way. Ultimately, users want to retain the ability to use more direct ways to attract attention as it might be needed in situations of emergency. However, in everyday life they preferred their smart wheelchair to maintain a more polite and empathetic style of communication with surrounding pedestrians, in the same way that they would normally interact using their voices or bodies.

This relates well with findings from previous studies examining the communication needs between different groups of road users, including smart vehicles, in shared spaces [56]. Suggestions from participants highlight how wheelchair users generally prefer to use more discrete visual means, such as light projections or small screens mounted on the armrest, to both give and receive feedback in most situations. As seen in both Li et al. (2021) [56] and Asha et al. (2021) [3] audio cues might be considered acceptable in emergency situations, where one needs to call immediate attention of surrounding pedestrians to avoid an immediate danger, but this mean of communication draws unwanted attention to the wheelchair users and was often seen as a last resort by participants. It is also important to remember that eHMIs might support the communication between wheelchair users and surrounding pedestrians in some situations, but users might deem them not necessary in many other circumstances. The survey carried out by Li et al. (2021) showed that many cyclist and pedestrian preferred to receive information and signals from car drivers through hand gestures, eye contact and head nods rather than headlights flashing or horns beeping [56]. It is reasonable to expect that in many social shared space these preferences for human communication without the mediation of eHMIs might translate to the interactions between smart wheelchairs and pedestrians.

Finally, as shown by the two scenarios described in Study 2, smart wheelchairs are likely to be used in much more various situations compared to most other types of semi-autonomous vehicles. This has direct consequences on both internal and external feedback systems, as considerations about what are socially acceptable ways to interact are significantly different depending on the situation [1, 74, 76]. Hence, interaction systems for smart wheelchairs need to incorporate a degree of flexibility to ensure that users are able to customise the way the smart wheelchair communicates with themselves and others in a way that feels appropriate to the context.

6.2 Situational Awareness and Adaptability

Situational awareness and adaptability are possibly the two most important key features for smart wheelchairs' interaction systems that we have identified across the two studies. As mentioned in the previous section, in order to be effective, smart wheelchairs need to be suitable for use across a variety of indoor and outdoor environments and in a multitude of different social situations. This requires control and interaction systems to incorporate a great degree of flexibility to accommodate the requirements associated with different scenarios. Moreover, smart wheelchairs also need to be able to respond to the shifting capabilities and the changing preferences of users adapting not only their mode of interaction, but also the degree of assistance provided to the individual.

Of course it is always possible to make these systems completely open and fully customisable, enabling users to continuously select their preferred combination depending on their personal state, the characteristics of the environment and the social context. However, although some users might be happy to be able to choose every single interaction and control aspect of their smart wheelchair, others might find this excessive degree of customization overwhelming, and prefer to be presented with simpler and more intuitive decisions [12, 47, 58]. To strike a balance between customization and user burden and to promote more seamless navigation experiences as smart wheelchairs transition across different environments, we advocate for the use of ability-based design approaches and sense-model-adapt design patterns [94, 95]. By embedding smart wheelchairs with sensory capabilities that go beyond what might be currently needed to ensure the choice of safe path for navigation, it should be possible to enhance the contextual awareness of the system, facilitating the transition between different modes of use depending on the affective state of the user and the situational context. The implicit personalized user model proposed by Vanhooydonck and colleagues offer a good starting blueprint for such a system [85]. The personalised user model would feature standard "smart driving" modes, such as zero assistance, which leaves the user in full control, or obstacle avoidance, which automatically modifies the path selected by the user in order to drive around a detected obstacle. However, specific smart driving modes can also be added and created by integrating information from users and ambient sensors that are integrated in the wheelchair [85]. For example, the physiological signal from an activity monitor might signal that the heartbeat of the user is slowing down significantly, which might indicate tiredness. This would signal the need for the smart wheelchair to increase the level of assistance provided, to make sure that the person is safe. Similarly, light sensors placed on the wheelchair might be used to detect conditions where lighting is poor which might require increased assistance or be more suitable to visual eHMIs such as projected light to signal one's presence to surrounding pedestrians. Although the user should always retain the ability to change and modify any of these settings according to their preference if they wish to do so, the smart wheelchair should assist and facilitate these choices based on its situational awareness.

6.3 Selective information management

Although it is important for smart wheelchairs to be able to effectively communicate important information to both users and surrounding pedestrians, there is a need to carefully consider which information should be shared, how, and with whom. Previous studies have shown that being bombarded with excessive information in a short space of time can lead to overload, which negatively affects an individual's performance [34]. Mahadevan et al. (2018)'s study examining interactions between autonomous vehicles and pedestrians showed that receiving too many cues, or cues with too many states that might be difficult to interpret, is more likely to cause information overload, especially when these cues rely on different sensory channels [61]. Similarly, in our study, participants expressed the preference towards having only selected information relevant for driving the smart wheelchair displayed by the interface at all time, whereas any other cue concerning potential obstacles should only be provided at the appropriate time needed to prevent collision in order to not overload the user as well as the surrounding pedestrians. Moreover, some participants also mentioned that they want to be given the ability to switch on and off any non-essential cue as they desire. Furthermore, although in the scenarios explored we assumed that our potential user Ann had unimpaired sensory and cognitive capabilities, it is important to remember that this might not be necessarily be true for all users or pedestrians at all times. For example as identified by Asha et al. (2021) [3], a wheelchair user with reduced visual capabilities might prefer to receive feedback about surrounding obstacles using haptic feedback rather than visual clues. Similarly, in conditions of intense sunlight such cues might not be visible to anyone regardless of their personal capabilities [3]. Moreover, a user with reduced cognitive capabilities might still want to receive feedback about the path of the wheelchair, but not necessarily about the type and location of detected obstacles to make the flow of information easier to understand [87]. Ultimately, although providing various cues in mixed modalities could potentially improve the decision-making performance for a wider range of people, this should be designed flexibly and with care in order to comply with situational and personal requirements and manage any potential risk for information overload.

Finally, while state-of-the-art interaction designs between autonomous vehicle and pedestrians include the need for information related to the recognition of pedestrians, explicit suggestions for pedestrians, the vehicle state and the vehicle intent, we only observed the need for the latter two when it came to smart wheelchair navigation in crowded environments [3, 27, 61]. This is possibly due to the different dynamic between an autonomous vehicle and a smart wheelchair in relation to pedestrians. While the former usually crosses through a crowd of pedestrians, the latter is more likely to move along with the pedestrian flow. Hence, the need for negotiating the road use through recognition and suggestions is less, whereas the need for mutually understanding has increased for better collaboration.

7 LIMITATIONS

While the target populations of the intelligent powered wheelchairs includes people who are not suitable to use a standard power wheelchair, our study sample was biased toward current power wheelchair users. In addition, the results presented could include gender bias as only one female participant was included in our second study.

8 CONCLUSION

Navigation in crowds involves a complex interaction between the wheelchair user and the other pedestrians. Shared control create additional complexities to the user-wheelchair interaction. By conducting a series of semi-structured interviews followed by a design workshop, we explored for the first time the user needs for shared control wheelchair driving in crowds and presented preliminary results for building two interaction loops in four themes: Type of information needed, interaction modality, interface location and adaptable design. Through reflections and comparisons to other work, we further proposed a series of design implications which includes: 1) Empathy, embodiment and social acceptance, 2) Situational awareness and adaptability and 3) Selective information management.

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