

Interactive Public Displays and Wheelchair Users: Between Direct, Personal and Indirect, Assisted Interaction

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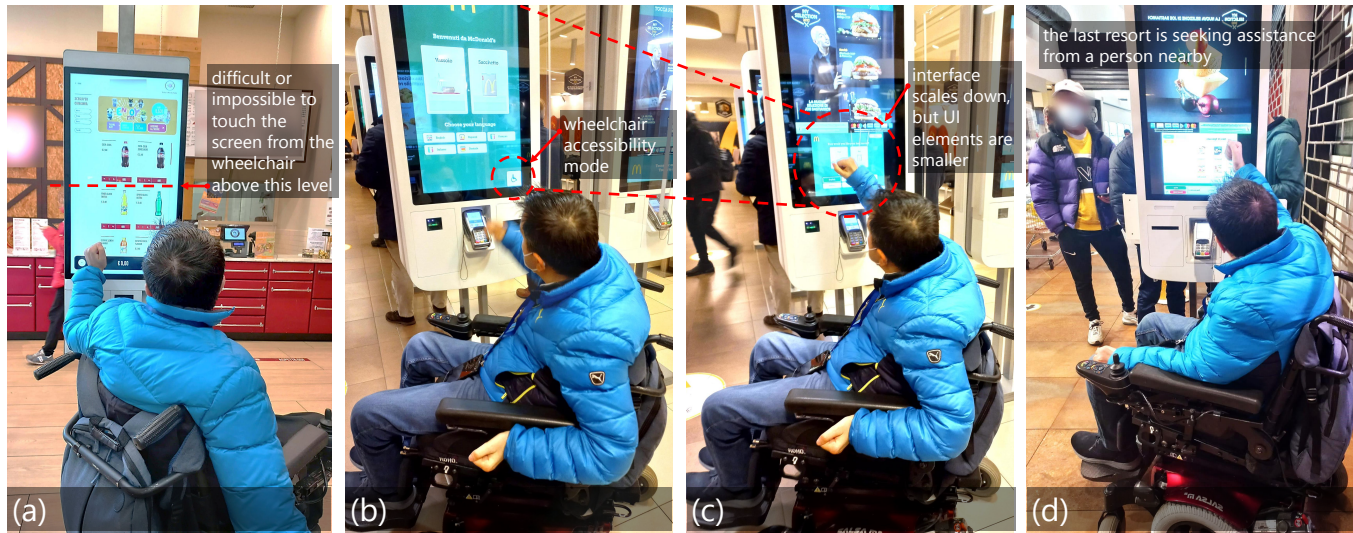


Figure 1: Two major accessibility challenges for wheelchair users when interacting with public displays are reaching to content that is positioned too high on the display and accurately selecting on-screen targets with touch input. For example, the upper part of the public display shown in the figure (a) cannot be reached comfortably from the wheelchair. Public displays that implement accessibility options, such as the one shown in figure (b), scale down the user interface, but the UI elements become smaller and more difficult to touch (c). The last resort is seeking assistance from someone nearby (d).

ABSTRACT

We examine accessible interactions for wheelchair users and public displays with three studies. In a first study, we conduct a Systematic Literature Review, from which we report very few scientific papers on this topic and a preponderant focus on touch input. In a second study, we conduct a Systematic Video Review using YouTube as a data source, and unveil accessibility challenges for public displays and several input modalities alternative to direct touch. In a third study, we conduct semi-structured interviews with eleven wheelchair users to understand their experience interacting with public displays and to collect their preferences for more accessible input modalities. Based on our findings, we propose the “assisted

interaction” phase to extend Vogel and Balakrishnan’s four-phase interaction model with public displays, and the “ability” dimension for cross-device interaction design to support, via users’ personal mobile devices, independent use of interactive public displays.

CCS CONCEPTS

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

KEYWORDS

Wheelchair users, motor impairments, mobility impairments, public displays, ambient displays, accessible input, study, systematic literature review, systematic video review, interviews

ACM Reference Format:

Radu-Daniel Vatavu, Ovidiu-Ciprian Ungurean, and Laura-Bianca Bilius. 2022. Interactive Public Displays and Wheelchair Users: Between Direct, Personal and Indirect, Assisted Interaction. In *The 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*, October 29–November 2, 2022, Bend, OR, USA. ACM, New York, NY, USA, 17 pages. <https://doi.org/10.1145/3526113.3545662>

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UIST '22, October 29–November 2, 2022, Bend, OR, USA

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ACM ISBN 978-1-4503-9320-1/22/10...\$15.00
<https://doi.org/10.1145/3526113.3545662>

1 INTRODUCTION

Interactive public displays are becoming increasingly prevalent as they integrate the physical environment with a variety of form factors [47,79]. Modern interactive displays engage people’s attention in a variety of ways [60], making passers-by transition to users and consumers of the content shown on the display [10,20,87]. Moreover, the interactive display market¹ is expected to grow further due to the increased adoption of applications for street and building signage, way-finding, ticketing, and the retail sector.

A large part of this market is represented by touchscreen displays² that enable simple, direct interaction. However, the “simple” act of touching on-screen targets involves complex visuomotor coordination of the arm, wrist, hand, and fingers. For people with upper-body motor impairments, touch input brings about a variety of accessibility challenges, from raising the arm to landing a finger on the screen to lifting the finger without sliding. For wheelchair users, parts of the screen may not be reachable from the wheelchair, the pathway to reach the public display with the wheelchair may be little accessible, or there may not be sufficient room in front of the public display to easily position the wheelchair. Such accessibility challenges still exist, even when access to public services and facilities is enforced by legislation,³ because “designers and developers make assumptions from their own abilities, from the ones they imagine other people have, or the ones of the supposed ‘average user’” [90] (p. 63). This “average user” is virtually present in the accessibility challenges illustrated in Figure 1, where the actual person in front of the display is a wheelchair user with Spinal Cord Injury at cervical vertebrae C4–C5 and with specific motor abilities. The figure shows two major accessibility challenges for wheelchair users when interacting with public displays. The display from Figure 1a shows content that is located too high to reach from the wheelchair, and offers no accessibility option. The second display (1b) offers the option to scale down the user interface so that wheelchair users can reach all of the content (1c), but the UI elements also become smaller and, because of that, more difficult to touch accurately. Figure 1d shows the last resort when the display is little or not accessible: seeking assistance from a person nearby.

In the tension between independent and assisted use of the public display lies the interactive experience of wheelchair users. Unfortunately, the scientific literature is scarce on the topic of interactions with public displays for users with motor and mobility impairments, in contrast to the large body of accessibility research conducted for other categories of computer systems [45] and the large body of work on public interactive displays [3] addressing the “average user.” This unfortunate state of things prevents sustained innovation, grounded on scientific evidence, towards more accessible interactions with public displays for users with various motor abilities. In this context, we make the following contributions:

- (1) We conduct a Systematic Literature Review study about interactive public displays and wheelchair users. We find

little scientific results on this topic and a preponderant focus on touch input for interacting with public displays.

- (2) We conduct a second study on the same topic, but with YouTube as the data source, i.e., a Systematic Video Review. We confirm touch as the predominant input modality, and report insights on accessibility challenges of public displays from the perspective of users with motor and mobility impairments as well as the perspective of their assistants.
- (3) To complete our findings, we conduct semi-structured interviews with eleven wheelchair users to document their experiences with interactive public displays, and we highlight the need for human assistance during interactions with displays not designed to be accessible in the first place. We also elicit preferences for alternative, more accessible input modalities for public displays compared to touch input, and report a high preference for smartphone-based solutions.
- (4) Based on our findings, we propose two implications for future work on accessible interaction design for public displays and wheelchair users: (i) an extension of Vogel and Balakrishnan’s [87] four-phase interaction model for public displays with the “assisted interaction” phase, where the public display supports by design the use case involving the primary user (from the wheelchair) and a secondary user (the assistant), and (ii) an extension of Brudy *et al.*’s [11] taxonomy of cross-device interaction with the “ability” dimension that connects cross-device with ability-based design [91] towards leveraging users’ specific motor abilities and their personal devices for independent use of interactive public displays.

2 RELATED WORK

We relate to prior work on interaction techniques for public displays and to prior research on accessible computing for users with motor impairments, at the intersection of which lies the scope of our work.

2.1 Interaction with Public Ambient Displays

A variety of input modalities have been proposed in the scientific literature for interactive public displays. These include touch input [19,61,87,88], pointing and mid-air hand gestures [38,58,84,87], feet gestures [37,70], whole-body [68,74,83], voice [15], eye gaze [40,96], and smartphone-based input [16,17,36,42,62], among others [3]. For example, Zadow *et al.* [88] introduced “SleeD,” a technique combining touch input on a wall display and an arm-mounted touchscreen worn as a sleeve to facilitate personalized interactions with large displays; Vatavu [84] presented “Smart Pockets,” an interaction technique leveraging body-referenced gestures for fast access to personal content on public displays; Shoemaker *et al.* [74] employed users’ shadows as interaction metaphors to facilitate content manipulation over large distances on the display; Jota *et al.* [37] proposed foot gestures for the lower part of the display; and Terenti and Vatavu [80] examined vibrotactile feedback delivered on the finger, wrist, and forearm to enrich the experience of touch input with public displays. One conclusion emerging from these examples is the rich diversity of input modalities available for interacting with public displays. For other examples, we refer to Ardito *et al.*’s [3] survey. Also, cross-device interaction involving mobile devices [16,17,36,42,62] has equally been proposed for

¹Many market reports are available, e.g., <https://www.marketsandmarkets.com/Market-Reports/interactive-display-market-36223528.html>.

²<https://www.marketsandmarkets.com/Market-Reports/multi-touch-nui-technology-market-459.html>; see footnote 1.

³For example, the Americans with Disabilities Act of 1990 (<https://www.ada.gov>) prohibits discrimination against individuals with disabilities in all areas of public life, including facilities open to the general public.

ambient displays. We connect to this interaction paradigm in Section 6, where we propose the “ability” dimension to extend Brudy *et al.*’s [11] cross-device design space.

A complementary research direction has been examining user behavior in front of and with public ambient displays. Narzt *et al.* [60] proposed a model for estimating collective human attention towards a public display with three user categories: users who ignore the display, watch the display, and are ready to interact with the display. Vogel and Balakrishnan [87] proposed a four-phase interaction model—*ambient display*, *implicit*, *explicit*, and *personal interaction*—to characterize transitions from implicit to explicit, public to personal interaction for multiple users. In the *ambient display* phase, users can get a sense of the information from the display with a quick glance; in the *implicit interaction* phase, the display employs information about the users’ body position and orientation as predictors for user interruptibility; in the *subtle interaction* phase, the display presents personalized information to the user that has approached the display; in the *personal interaction* phase, the user is close enough to the display to touch it and access personal information. We extend this model in Section 6 with the *assisted interaction* phase for wheelchair users.

2.2 Accessible Computing

A large body of scientific literature exists on designing accessible interactions for users with motor and mobility impairments and desktop computers [24,26,63,72], mobile devices [2,33,39,54,55,59,82], and wearables [49,50,77,81]. For example, Findlater *et al.* [24] and Sharif *et al.* [72] examined mouse pointing, Montague *et al.* [54] documented mobile touchscreen use, Malu *et al.* [50] examined the accessibility of head-mounted displays, and Vataavu and Ungurean [86] reported gesture input performance with smartwatches, smartglasses, and smart rings for users with motor impairments. For other examples, we refer readers to surveys [45,76,77] of accessible computing and assistive technology for users with motor and mobility impairments. Unfortunately, scientific papers on the topic of interactive public displays are scarce, as we show in Section 3.

One approach to accessibility is designing systems that adapt to users’ specific abilities. For example, Gajos *et al.* [26] introduced SUPPLE and SUPPLE++, two systems that employ users’ preferences and model users’ motor abilities to automatically adapt the UI, and Schipor *et al.* [71] proposed a machine learning approach that leverages users’ self-reported motor impairments and symptoms to provide accurate recommendations for personalized input modalities for wearables that match 85.3% with users’ own preferences. Ability-based design [90,91] is an approach to designing accessible computer systems that encourages designers to focus on users’ abilities rather than disabilities towards interactive systems better matched to those abilities. We capitalize on ability-based design in Section 6 to propose the “ability” dimension for cross-device interaction with public displays via users’ mobile devices.

3 SYSTEMATIC LITERATURE REVIEW STUDY

We conducted a Systematic Literature Review (SLR) study to identify scientific work on interactive public displays and wheelchair users. Unlike conventional literature reviews that involve selective

discussion of papers related to a given topic, SLRs are methodical, transparent, replicable, and comprehensive syntheses of the available scientific evidence on the respective topic [75].

3.1 Procedure

Following Siddaway *et al.*’s [75] recommendations for conducting SLRs, we implemented the identification, screening, and eligibility stages. During identification, we ran queries in the ACM DL and IEEE Xplore electronic databases, two major sources of Computer Science scientific papers, using a set of search terms identifying both the user category and the interactive technology constituting the scope of our work. The following query:

```
"query": {
  Fulltext: (wheelchair OR "motor impair*" OR "motor disab*")
  AND Fulltext: (kiosk* OR "public display*"
                OR "ambient display*"
                OR "interactive display*")
} "filter": { ACM Content: DL }
```

returned 106 results from ACM DL and 114 from IEEE Xplore.⁴ In the next stage, we screened the paper titles and abstracts and removed papers not relevant to our scope, but which were returned by our queries because the search terms appeared in their full text, although were not central to their topic. Examples include discussing related work about wheelchair users or public displays [13,51,69]. For the papers with relevant topics, we applied the following eligibility criteria (EC₁ to EC₅):

- EC₁: *Availability*. Full text is available and the paper is in English.
- EC₂: *Peer-reviewed references only*. The paper is academic and peer reviewed, e.g., conference papers, journal articles. We excluded descriptions of proceedings, calls for papers, etc.
- EC₃: *Specificity to the target user category*. The paper is about or mentions people with motor or mobility impairments.
- EC₄: *Specificity to the target systems*. The paper is about public ambient displays.
- EC₅: *Specificity to interactions*. The paper presents, evaluates, or discusses interactions with public ambient displays.

After the eligibility stage, we arrived at a dataset of twenty academic papers [3,6–8,14,18,27–29,31,44,56,64–67,73,78,93,95],⁵ from which two researchers extracted information (see Subsection 3.2 for our measures) and confronted results. We quantified their consensus using Gwet’s AC1 [30] inter-reliability coefficient,⁶ which computed

⁴For IEEE Xplore, the query was: (“Full Text & Metadata”:wheelchair OR “Full Text & Metadata”:“motor impair*” OR “Full Text & Metadata”:“motor disab*”) AND (“Full Text & Metadata”: kiosk* OR “Full Text & Metadata”: “public display*” OR “Full Text & Metadata”: “ambient display*” OR “Full Text & Metadata”: “interactive display*”).

⁵Of these, two papers [8,93] did not feature public displays in the strict sense of the concept: Wobbrock *et al.* [93] evaluated text entry performance with a power wheelchair joystick and touchpad using a laptop, and Bilius *et al.* [8] presented the example of a person with Spinal Cord Injury interacting with the display of a smart washing machine via an NFC ring. However, we included these two papers in our dataset due to the context in which their contributions were introduced, i.e., Wobbrock *et al.* [93] mentioned “As more public information terminals (kiosks) appear in building lobbies and libraries, on streets, in subways, and in community centers, the ability to access these terminals becomes more important [...] It would be advantageous to have an integrated control system where the power wheelchair joystick or touchpad could be used as the input device for mousing and text entry for such terminals” (p. 111), and Bilius *et al.* [8] noted “Most smart ring products feature NFC functionality that enables mobile users to authenticate, access premises, and make payments fast and effortlessly. Such features are convenient for people with motor impairments, since they enable simple interactions compared to other types of public display UIs” (p. 124).

⁶AC1 is a more stable coefficient of agreement than Cohen’s κ ; see [30]. We used the irrCAC R package (<https://cran.r-project.org/web/packages/irrCAC/>) to compute AC1.

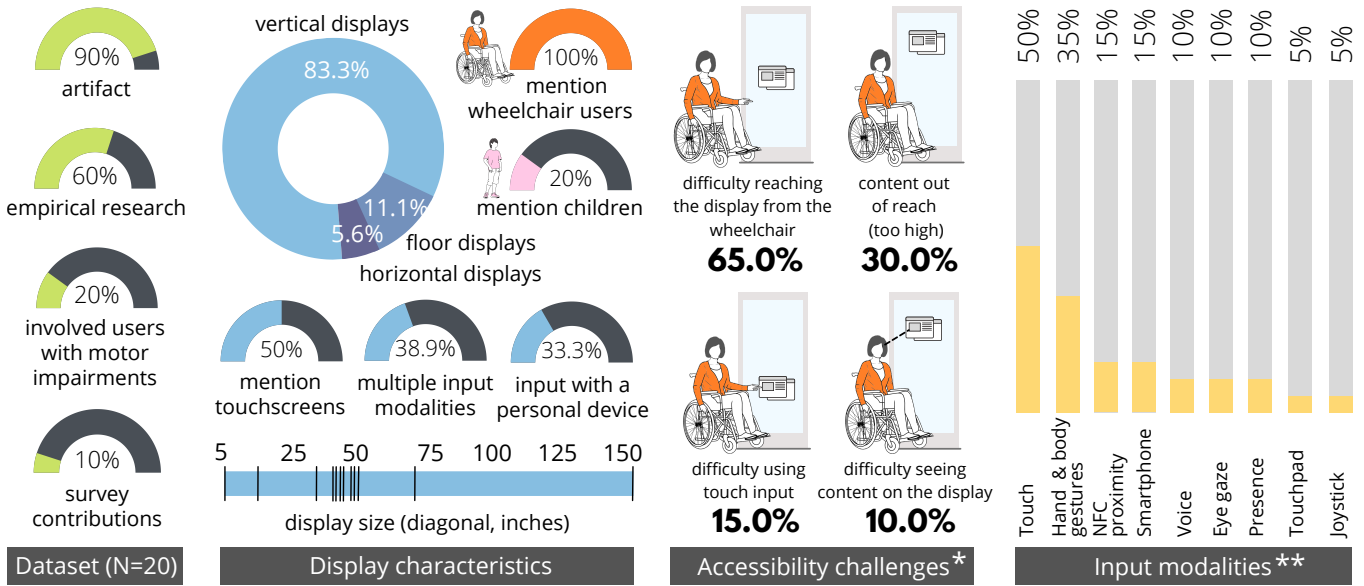


Figure 2: Summary of the results from our Systematic Literature Review (SLR) study.

to .899, a value indicating a consensus level between “substantial” and “almost perfect,” according to the Landoch-Koch benchmarking scale⁷ (.988 cumulative membership probability). Differences were discussed and, when consensus could not be reached by the two coders, the differences were settled using majority voting by the intervention of a third researcher.

3.2 Measures

We extracted the following information, representing measures in our study, by employing and adapting to our scope the classification dimensions from Ardito *et al.*'s [3] survey of interactive displays:

- Information about the display setup, for which we extracted ORIENTATION (*vertical, horizontal, diagonal, or floor*), SIZE (e.g., 50-inch diagonal), and TOUCH-CAPABILITY (*yes/no*).
- The INPUT-MODALITY implemented by the public display, e.g., *touch, voice, mid-air gestures, smartphone input*, etc.
- Information about the ACCESSIBILITY-CHALLENGE addressed or mentioned in the paper.
- Information about whether ASSISTANCE was needed from another person (*yes/no*) to interact with the public display.
- Information about user characteristics, for which we extracted (i) NUM-PARTICIPANTS, the number of people with motor or mobility impairments included in the user study for papers reporting such studies, (ii) the AGE-GROUP (*child or adult*) and (iii) the HEALTH-CONDITION of the target end users of the interactive public display.

We also used Wobbrock and Kientz's [92] categories of research contributions in HCI to characterize the papers from our dataset,

e.g., an artifact contribution may represent a prototype of an interactive display, interaction technique, or design proposal, while papers with empirical contributions report the results of a study.

3.3 Results

Figure 2 presents an overview of our results. We found two survey papers [3,6], eighteen papers (90.0%) presenting artifacts at various stages of implementation, from design proposals [8,67] to functional prototypes [7,31,95] to systems evaluated with users [14,44,56,93], and twelve papers (60.0%) with empirical research contributions.

We first focused on the two surveys [3,6], but found little information about accessible public displays. Ardito *et al.*'s [3] survey on interactions with large displays included only a brief subsection on accessibility, centered on people with visual impairments, and concluded about the scarcity of research on motor impairments: “Most research is focused on supporting visually impaired users, but other disabilities should be considered. For instance, people in a wheelchair cannot interact with vertical displays; interaction modalities based on remote devices or gaze control might provide a support for this type of disability” (p. 46:27). The other survey [6] on public transportation displays offered only a brief detail: “To support accessibility for passengers with physical disabilities, the screen features a button to read aloud connections for the visually-impaired and a button to move the entire digital content towards the bottom of the screen for passengers in wheelchairs” (p. 40).

After reading the rest of the eighteen papers from our dataset, we reached the same conclusion as Ardito *et al.* [3] about very little scientific results on public displays and users with motor or mobility impairments. We found just a handful of papers [31,56,64,65] describing prototypes of accessible displays, while the large majority of the papers from our dataset briefly mentioned wheelchair users

⁷<https://cran.r-project.org/web/packages/irrCAC/vignettes/benchmarking.html>.

as part of the end users of the displays they featured. For instance, Prandi *et al.* [67] presented several design proposals for interactive technologies for bus stops, and mentioned that “Accessibility [of the public display] was implemented providing wheelchair users with a platform lift” (p. 20:4); Sorce *et al.* [78] presented Kinect-based mid-air gesture interaction with an information access point and noted that “wall-sized displays may become interactive even if they are unreachable by touch [...] people with temporary or permanent physical impairment (e.g. wheelchair users) may still comfortably interact with the display” (p. 37); and Zhai *et al.* [95] presented touch and mid-air input with a wall display, and noted “As a large display is generally taller than people, it is uncomfortable for certain users to reach the upper part of the display and even impossible for some young users or users on wheelchairs” (p. 176). Other papers [7,18,27–29,73] included similar brief mentions without any reference to specific health conditions, motor, or mobility impairments. Nevertheless, we still used these papers in our analysis because they imparted, even if only briefly, their authors’ perspectives on accessibility challenges for the interactive displays featured in those papers. Returning to the previous examples, such accessibility challenges include difficulty reaching the display with the hand from the wheelchair in Prandi *et al.* [67], difficulty using touch input in Sorce *et al.* [78], and difficulty reaching content located too high on the display in Zhai *et al.* [95]. Overall, we identified twenty-five mentions of accessibility challenges of four distinct types; see Figure 2, middle right.

Of the papers that mentioned accessibility challenges, four [18,44,56,66] acknowledged ASSISTANCE from another person. Pous *et al.* [66] employed the average “number of requests for help” as a measure during their user study; Mott *et al.* [56] adjusted the height of the interactive tabletop for each wheelchair user from their study; Dalton [18] commented that wheelchair users might find their interactive floor difficult to use without assistance; and Lim *et al.* [44] documented interactive floor use in a hospital: “Children in wheelchairs were also observed driving themselves over the pond to see how it reacted. A few tried to interact with it by stretching out their arms and legs while in their wheelchair [...] For children who could not try because of their physical condition, but wanted to have a go, parents often helped out by supporting their body or demonstrating, themselves, to show how it worked” (p. 9:11).

Most of the displays from the eighteen papers with artifact contributions had vertical ORIENTATION (15/18=83.3%), two were interactive floors [18,44], and one was a tabletop [56]. Display SIZE varied greatly, from a few inches [8,93] to 40- and 50-inch displays to a large 157-inch wall display [95] ($M=49.6$, $SD=37.8$, coefficient of variation $CV=0.8$). A percent of 50.0% of the displays were touchscreens [8,14,29,31,56,64,65]. Other INPUT-MODALITY categories included mid-air gestures [27,28,64,65,73,78,95], NFC-based input [8,64,65], smartphone-based solutions [7,14,66], voice [14,66], eye gaze [14,66], presence sensing [18,44], and a touchpad and joystick [93], respectively; see Figure 2, right.

Twelve papers reported user studies, but only four [14,56,66,93] actually included users with motor or mobility impairments: people with Amyotrophic Lateral Sclerosis [14], Cerebral Palsy [56,93], Multiple Sclerosis [56,93], and Spinal Cord Injury [56]. Regarding AGE-GROUP, all of the papers with artifacts and/or empirical research addressed adults, and four [29,31,44,64] mentioned children.

Of the latter, Lim *et al.* [44] addressed children primarily with an interactive floor display meant to reduce anxiety in a hospital.

3.4 Takeaways

Our SLR showed very little scientific examination of public displays and wheelchair users. Observations about accessibility challenges were scarce and brief, and interaction techniques were largely intended for users without motor or mobility impairments. To find out more, we turned to another data source; see next.

4 SYSTEMATIC VIDEO REVIEW STUDY

We conducted a second study using YouTube as the data source to learn more about accessibility challenges of public displays from videos featuring users with motor and mobility impairments. Analyzing YouTube videos represents a fruitful method in HCI research to learn about users [2,9,32,35]. We implemented the study by running queries on YouTube to identify relevant videos just like we used queries in our SLR to identify scientific papers. Due to this similarity, we refer to our study as a Systematic Video Review (SVR).

4.1 Procedure

Following Anthony *et al.* [2], we adopted their list of search terms describing motor impairments and health conditions, $S_1=\{\text{assistive technology, brain injury, cerebral palsy, Friedreich ataxia, hemiplegia, Lou Gehrig, motor disability, motor disabilities, motor impairment, motor impairments, multiple sclerosis, muscular atrophy, muscular dystrophy, paraplegia, Parkinson's, quadriplegia, spina bifida, spinal cord injury, tremor, wheelchair}\}$, and we defined a second list with search terms about public displays, $S_2=\{\text{ambient display, digital signage, kiosk, interactive table, public display, touch screen, touch screens}\}$. By considering all the pairs from the Cartesian product $S_1 \times S_2$, we ran a total number of $20 \times 7 = 140$ queries that resulted in a list of 9,274 videos. We used the incognito mode from Chrome to prevent any influence on the search results of the prior web activity of the researcher’s Google account.⁸ We excluded duplicates (the same video returned by multiple queries because of multiple matching search terms), and applied the following eligibility criteria (EC₁ to EC₃) to filter out videos not relevant to our scope:

- EC₁: *Specificity to the target user category.* The video features people with motor or mobility impairments.
- EC₂: *Specificity to the target systems.* The video features a public display. Some of the videos returned when using the search term “display” were about personal displays, such as PCs or custom computers with built-in assistive technology used in a home environment, which we excluded. We also excluded videos of rehabilitation technology used in clinics that were returned by our queries because they employed a display. Also, we excluded videos featuring mobile devices, e.g., smartphones, tablets, laptops, and screens mounted on the wheelchair, which were returned by the search terms “touch screen” and “touch screens,” respectively.
- EC₃: *Specificity to interactions.* The video illustrates interactions with a public display.

⁸According to <https://support.google.com/youtube/answer/6342839>, “Your activity on YouTube, Google, and Chrome may influence your YouTube search results, recommendations on the home page, in-app notifications, and suggested videos.”

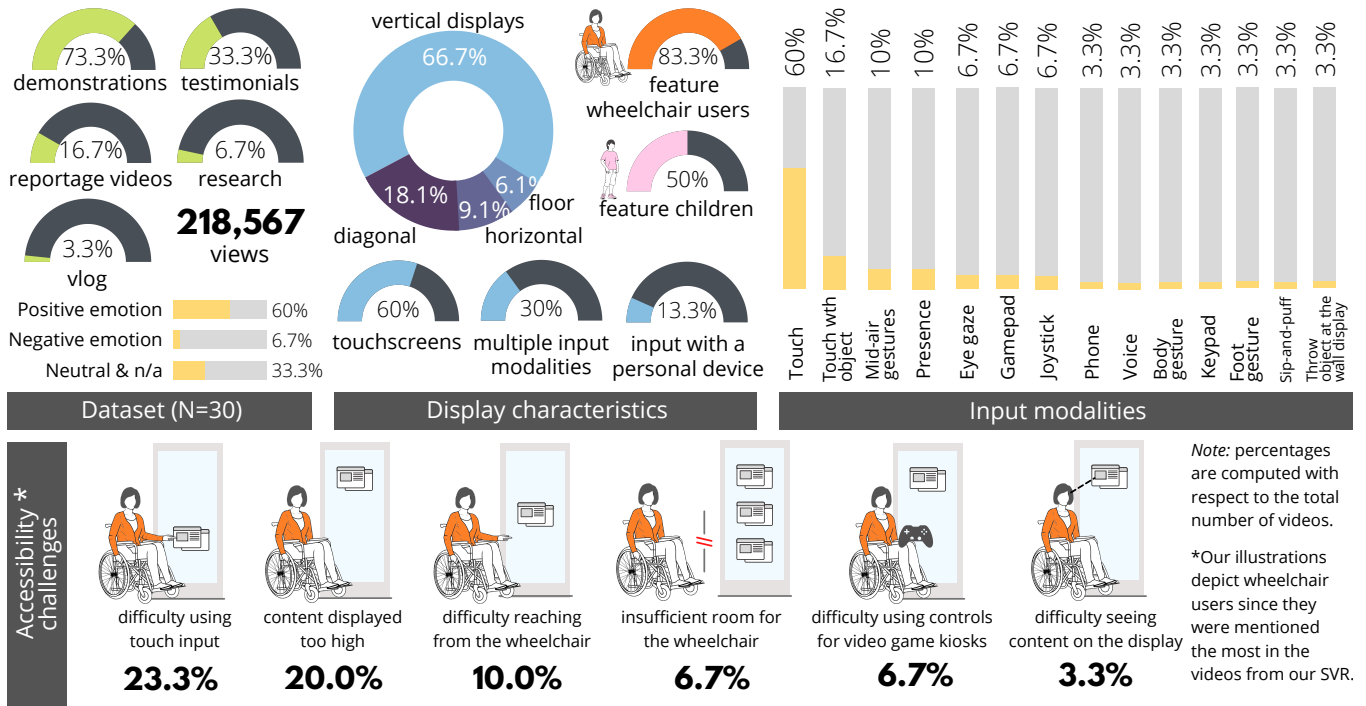


Figure 3: Summary of the results from our Systematic Video Review (SVR) study.

After applying the eligibility criteria, we arrived at a dataset of thirty videos with a combined duration of 99.8 minutes ($M=3.3$, $SD=3.4$) and a total number of 218,567 views until the date of our study. Two researchers extracted information from the videos (see Subsection 4.2 for our measures) and confronted results. Gwet's [30] AC1 was .861, indicating a "substantial" level of consensus according to the Landoch-Koch benchmarking scale (.984 cumulative membership probability). The differences were discussed and, when consensus could not be resolved by the two coders, were settled with majority voting by the intervention of a third researcher.

4.1.1 Ethical considerations. Even if YouTube videos are publicly shared, we took the following precautions to protect the privacy of their authors and the people appearing in the videos: (i) we kept a list of URLs without downloading the videos, (ii) we refer to the videos in this paper by their IDs, e.g., V_3 denotes the third video from our dataset, and we do not reveal any identifying information, such as title, author, or URL; in doing this, we respect the authors' right to remove their videos at any time, after which the URLs will no longer be valid; (iii) we do not use snapshots from the videos in the presentation of our results; (iv) we anonymize quotes from the videos by removing references to names, places, time, and events.

4.2 Measures

As in our SLR study (Subsection 3.2), we extracted information about display ORIENTATION, TOUCH-CAPABILITY, INPUT-MODALITY, and ACCESSIBILITY-CHALLENGE, and the AGE-GROUP and HEALTH-CONDITION of the users featured in the videos. We also extracted the following information to characterize our video dataset:

- VIDEO-CATEGORY, for which we used an adaptation of the categories employed by Blythe and Cairns [9]: *testimonial* (i.e., commercial video presenting the experience of a user), *product demonstration* (of a public display or assistive technology to use with a public display), *reportage* (a journalistic presentation of an account, e.g., about the inaccessibility of public displays), *research* (an accessible display or interaction technique from a research project), and *vlog* (user-generated video showing interactions with a public display). Multiple categories are possible for a video, e.g., a *product demonstration* accompanied by the *testimonial* of a user.
- VIDEO-EMOTION (*positive*, *negative*, *neutral*), inspired from [2, 32], which we computed automatically from the text description of the YouTube videos using a sentiment analysis tool.⁹

4.3 Quantitative Results

Figure 3 presents an overview of the results from our SVR. Most of the videos from our dataset were demonstrations (22/30=73.3%) and testimonials (10/30=33.3%) with descriptions revealing mostly positive (60.0%) emotions. Just like in the SLR study, a large proportion (83.3%) of the content addressed wheelchair users. Specific health conditions included Cerebral Palsy (26.7%), Spinal Cord Injury (6.7%), Multiple Sclerosis (3.3%), and Spina Bifida (3.3%).

We identified twenty-two mentions of accessibility challenges, which we grouped into six categories (Figure 3, bottom), of which four already emerged in the SLR study. The most frequent accessibility challenge was using touch input (23.3%) followed by reaching to content located too high on the display (20.0%). More than half

⁹<https://monkeylearn.com/sentiment-analysis-online> using the model cl_pi3C7JiL.

of the videos (56.7%) featured ASSISTANCE from a family member or health professional.

Vertical displays were the most common (66.7%), and 60.0% of the displays were touchscreens. Overall, the displays from our video dataset featured between one and four input modalities ($M=1.4$, $SD=0.7$) with touch being the most common; see Figure 3, top right. However, touch input was challenging to use because of spastic hands and joint stiffness caused by Cerebral Palsy, the use of different fingers after an injury, and reduced finger motricity and tremor because of the shoulder-hand syndrome for users recovering after a stroke. Touch input was also implemented with assistive objects, such as a small disk held between the fingers, a pen, a large object held with both hands, or a hand stick, depending on the application and the health condition of the user. Other input modalities were present to a lesser degree: smartphone, presence sensing for interactive floors and in front of a wall display, and body gestures performed from the wheelchair.

4.4 Qualitative Findings

Not all of the videos contained dialogue and, when they did, interactions with public displays were featured just briefly and were rarely accompanied by dialogue. However, the few quotes that we were able to extract from our video dataset provide valuable insights into users' perceptions of accessibility challenges, which we report in the following to complement the quantitative results from Figure 3. The quotes explicitly mention accessibility challenges, suggest possible workarounds, or express feelings resulting from the unsuccessful use of interactive public displays.

In a video with digital order kiosks at a restaurant, a wheelchair user says "The kiosk's display is too high. It would be nice if it came down" and "sometimes I had to move to another location because I couldn't reach the screen" (V₃, 0:37), revealing both a technical solution of a configurable height-adjusting display, but also a coping strategy, i.e., give up using the display to look for another one to be able to place the order. In a reportage about parking kiosks, a wheelchair user reports difficulties reaching the keypad. The reporter says "this parking meter like others around the city is in violation of the Americans with Disabilities Act. That's because the display panel is set up at 52 inches; she says it should be set up at 48 inches" (V₄, 0:25) and "on this one [parking meter], she can operate the keypad, but the display window is too high for her to read and confirm information" (V₄, 1:02). The wheelchair user tells a story when she paid for someone else's parking by mistake because she could not see the information from the display, and how she regularly asks for other people to feed the meter for her. The perception of the wheelchair user is that of a discrimination act, "It's discrimination. It's not just an architectural barrier, it's discrimination" (V₄, 0:52). Other videos show successful use of kiosks despite buttons being placed too high to reach comfortably from the wheelchair, sometimes at the limit of the user's stretching arm. In a vlog post, a wheelchair user says "actually, I've got this" (V₁₀, 8:46), after reaching for a button located too high on the display, to confirm to her companion independent use of the display.

Other videos revealed the desirability for input modalities alternative to touch to enable interactions with the public display from a distance, which would mitigate accessibility challenges experienced

when navigating towards the display, reaching the display with the hand, and touching buttons accurately. For example, in a reportage covering exhibits from an accessibility convention, the reporter, also a wheelchair user, tries out an interactive display controlled by body movements detected by the Kinect sensor and leans his body left and right in the wheelchair. He says: "I was bad at doing my therapy, but if it was like this [Kinect video game], I would definitely have done it more [...] I'm gonna come back cause I'm determined to do that level" (V₅, 8:10). In a demonstration video of an interactive space from a hospital designed to provide comfort and distractions from the moments of highest anxiety for patients, children use a smartphone app that shows interactive content in relation to the animated characters from the wall display. An adult patient says "things like this make kids more excited to be here instead of sitting in a boring hospital room doing nothing. They can interact with stuff and see familiar characters that they're used to that make them happy and see them come to life [on their smartphones]" (V₁₄, 1:04). In another video, also filmed in the lobby of a children's hospital, a large media wall reacts to the presence of people in front of it. The narrator describes the user experience that the hospital sought with this type of interaction as follows: "We were looking to create an environment and an experience where technology disappeared" (V₁₅, 0:46) and "What makes it work for people is it feels very human" (V₁₅, 2:04).

4.5 Takeaways

The results of our SVR study complement those of the SLR by confirming touch as the predominant input modality for interactive public displays and by providing insights on accessibility challenges from the end-user perspective. Although useful, this information is still limited because of the data source: few videos, mostly of commercial nature, despite our extensive search. For more information, we decided to conduct interviews with wheelchair users about their experiences interacting with public displays; see next.

5 SEMI-STRUCTURED INTERVIEWS STUDY

We conducted semi-structured interviews with wheelchair users to understand perceptions about their experiences with interactive public displays, but also to collect their preferences for more accessible input modalities for public displays.

5.1 Participants

Eleven people (nine male, two female), aged between 28 and 59 years ($M=42.9$, $SD=9.4$) took part in our study. We used convenience sampling and recruited participants via a non-profit association providing technical support to people with disabilities. Our inclusion criteria were: (i) participants were wheelchair users and (ii) they had used public displays prior to our study. Participants' health conditions were diverse, as reflected by the WHODAS 2.0 [94] health and disability scores¹⁰ ranging between 16.7 and 70.8 ($M=41.1$,

¹⁰WHODAS 2.0 is a generic assessment instrument for measuring health and disability that captures, in a direct connection with the International Classification of Functioning, Disability and Health, the level of functioning in six domains of life: cognition, mobility, self-care, getting along, life activities, and participation [94]. According to the normative data report of Andrews *et al.* [1] based on 8,841 respondents, individuals scoring between 20 and 100 on the WHODAS scale are in the top 10% of the population distribution likely to have clinically significant disabilities.

Table 1: Demographic details of the wheelchair users from our study, their self-reported impairments using the categories from Findlater *et al.* [24], and the corresponding WHODAS 2.0 health and disability scores [94].

Participant	Health condition [‡]	Functionality	Since	Self-reported impairments [†]												#	WHODAS
				Mo	Sp	St	Tr	Co	Fa	Gr	Ho	Se	Dir	Dis	2.0 score		
P ₁ (41 yrs., male)	Spinal Cord Injury (C4, C5)	Tetraplegia	2003	–	✓	✓	–	–	✓	✓	✓	✓	✓	✓	8	54.2	
P ₂ (40 yrs., male)	Spinal Cord Injury (T4)	Paraplegia	1998	–	✓	–	–	–	–	–	–	–	–	–	1	20.8	
P ₃ (43 yrs., male)	Traumatic Brain Injury	Tetraplegia	1996	✓	–	–	–	✓	✓	–	–	–	–	✓	4	43.8	
P ₄ (28 yrs., male)	Spinal Cord Injury (C6, C7)	Tetraplegia	2008	–	–	–	–	–	–	✓	–	–	–	–	1	27.1	
P ₅ (40 yrs., female)	Encephalitis	Tetraplegia	1980	–	✓	–	–	–	✓	✓	✓	–	–	–	4	22.9	
P ₆ (42 yrs., female)	Infantile Cerebral Palsy	Paraplegia	1978	–	✓	✓	–	–	–	✓	–	–	–	–	4	16.7	
P ₇ (44 yrs., male)	Spinal Cord Injury (C6, C7)	Tetraplegia	1998	✓	✓	–	–	✓	–	✓	–	✓	✓	✓	7	54.2	
P ₈ (59 yrs., male)	Spinal Cord Injury (T3, T4)	Paraplegia	1988	–	–	✓	–	–	✓	–	–	–	–	–	2	22.9	
P ₉ (58 yrs., male)	Spinal Cord Injury (C5, C6)	Tetraplegia	1998	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	10	70.8	
P ₁₀ (31 yrs., male)	Spinal Cord Injury (C5, C6)	Tetraplegia	2017	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	10	56.3	
P ₁₁ (46 yrs., male)	Spinal Cord Injury (C5, C6)	Tetraplegia	1994	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	10	62.5	
Summary				5	8	6	0	5	8	7	6	5	5	6	5.5	41.1	

[†]Mo = Slow movements; Sp = Spasm; St = Low strength; Tr = Tremor; Co = Poor coordination; Fa = Rapid fatigue; Gr = Difficulty gripping; Ho = Difficulty holding; Se = Lack of sensation; Dir = Difficulty controlling direction; Dis = difficulty controlling distance. [‡]The code in the parentheses denotes the affected vertebra(e), e.g., “Spinal Cord Injury (C6)” refers to a traumatic injury at the 6th cervical vertebra.

SD=19.5); see Table 1. The number of years since our participants had been living with their motor impairments varied between 3 and 42 (M=23.4, SD=11.6). Frequently self-reported motor impairments [24] included spasm (8 out of 11 participants), rapid fatigue (8/11), difficulty gripping (7/11), low strength (6/11), difficulty holding (6/11), and difficulty controlling distance (6/11). One of the participants (P₆) was primarily using a walker with seat and wheels and, occasionally, a manual wheelchair.

5.2 Procedure

We conducted one-to-one interviews over the phone,¹¹ which were structured using a Google Forms questionnaire to assist the interviewer to easily record participants’ responses, but also to make sure that the questions were presented identically to all of the participants. The interviews took about 45 minutes per participant.

5.3 Measures

We collected the following measures:

5.3.1 Demographic information. We asked our participants about their motor impairments and health conditions, which they reported using the eleven categories from [24], and we administered the WHODAS 2.0 [94] instrument; see Table 1 for the results.

5.3.2 Accessibility challenges. We measured the ACCESSIBILITY-CHALLENGE variable with yes/no responses to the following nine statements about potential accessibility challenges informed by our SLR and SVR studies: (1) “The pathway to the public display was not accessible for the wheelchair,” (2) “Not enough room in front of the public display for my wheelchair to fit in easily,” (3) “I had to move my wheelchair around the public display to be able to reach all of the content from the display,” (4) “Reaching the public display with my hand was difficult,” (5) “The interactive content was placed too high on the display,” (6) “The interactive content was placed

too low on the display,” (7) “The soft buttons were difficult to press,” (8) “The soft buttons were too small to touch accurately,” and (9) “The public display did not recognize my touches”; see Figure 4, top left for illustrations. The yes/no responses were referring to situations that our interviewees encountered at least once (a “yes” response) when using a public display, e.g., not enough room in front of the display during at least one interaction. The presentation order of the ACCESSIBILITY-CHALLENGE conditions was randomized per participant. Participants were also asked whether they had experienced other accessibility challenges, not covered by our list, when interacting with public displays.

5.3.3 Need for assistance. We measured ASSISTANCE with yes/no responses to the question “Have you ever needed help or assistance interacting with a public ambient display?” for each of the following conditions: (1) *assistance-not-needed*, “No, I was able to successfully interact with public ambient displays,” (2) *assistance-from-companion*, “Yes, I asked my companion for assistance,” (3) *assistance-from-employee*, “Yes, I asked an employee for assistance,” (4) *assistance-from-passerby*, “Yes, I asked a passer-by for assistance,” and (5) *assistance-unavailable*, “Yes, but I haven’t always had whom to ask for assistance.” The presentation order of the five conditions was randomized per participant.

5.3.4 Perception of the efficiency to interact with public displays. PERCEIVED-EFFICIENCY, measured with a 5-point Likert scale with items from 1 (“very inefficient”) to 2 (“inefficient”), 3 (“moderate”), 4 (“efficient”) to 5 (“very efficient”) in response to “How would you characterize your efficiency in interacting with public displays?”

5.3.5 Perception of unwanted attention. We measured UNWANTED-ATTENTION with a 5-point Likert scale with items from 1 (“strongly disagree”) to 2 (“disagree”), 3 (“neither agree nor disagree”), 4 (“agree”) to 5 (“strongly agree”) in response to “I feel I am drawing unwanted attention to my disability when using a public display.”

¹¹Social distancing measures were in force in various forms at the moment of the interviews. Also, our participants preferred remote participation.

5.3.6 Preference for input modalities to interact with a public display.

We collected usefulness ratings with 5-point Likert scales with items from 1 (“not useful”) to 2 (“little useful”), 3 (“moderately useful”), 4 (“useful”) to 5 (“very useful”) for each of the following conditions of the INPUT-MODALITY variable: (1) *smartphone-as-a-mouse*, i.e., using the touchscreen of the smartphone to control a mouse pointer on the public display, (2) *smartphone-app*, installing a dedicated smartphone app that offers the same functionality as the public display, (3) *cast-to-smartphone*, casting the screen of the public display to the smartphone, (4) *wheelchair-joystick*, using the wheelchair joystick to control a pointer on the public display, (5) *wheelchair-as-a-mouse*, moving the wheelchair in front of the display to perform selections, (6) *eye-gaze*, using eye gaze tracking to select options from the public display, (7) *EEG*, using an electroencephalography-based input device, e.g., a neural headset, to select options from the public display, (8) *mid-air-gestures* representing hand movements in mid-air in front of the display, (9) *head-gestures* representing movements of the head, and (10) *speech* input. We compiled these conditions by drawing inspiration from the findings of our SLR and SVR studies, but also from prior work on interactions with large displays; see Subsection 2.1. Figure 5 illustrates the motor abilities needed to use each of these input modalities. The order of INPUT-MODALITY was randomized per participant. Participants were encouraged to suggest other input modalities as well.

5.4 Analysis and Statistical Tests

We report medians as the conventional measure of central tendency for Likert-scale ordinal variables, which we complement with means and histograms to provide a comprehensive picture of our participants’ responses. We also employ nonparametric tests (Friedman and Wilcoxon) to compare medians, Spearman’s ρ coefficient for rank correlations involving ordinal variables, and Kendall’s τ coefficient for correlations involving a binary variable.

5.5 Quantitative Results

5.5.1 Accessibility challenges for interacting with public displays.

Most of our participants reported content located too high on the display (8/11=72.7%), difficulty reaching the screen with the hand (8/11=72.7%), and not enough room in front of the public display for the wheelchair (6/11=54.5%); see Figure 4, left. Other accessibility challenges, such as misrecognized touches or pressing soft buttons, were mentioned to a less degree. A Cochran’s Q test found a statistically significant effect of ACCESSIBILITY-CHALLENGE on participants’ responses ($Q_{(8)}=34.023, p<.001$). Despite these challenges, PERCEIVED-EFFICIENCY was high with a median of 4 ($M=3.5, SD=1.1$). However, the median of UNWANTED-ATTENTION was also 4 ($M=3.8, SD=1.2$), showing that interacting with public displays was perceived as drawing unwanted attention to our participants’ motor and mobility impairments. We found a statistically significant negative correlation between WHODAS-2.0 and PERCEIVED-EFFICIENCY ($\rho_{(N=11)} = -.714, p<.05$): participants with more advanced disability reported less efficient interactions with public displays. We also found a relatively high positive correlation between WHODAS-2.0 and UNWANTED-ATTENTION ($\rho_{(N=11)}=.567$), but which was not statistically significant ($p=.069>.05, n.s.$).

5.5.2 Need for assistance. We found a statistically significant effect of ASSISTANCE on participants’ responses ($Q_{(4)}=21.6, p<.001$); see Figure 4, right. The large majority of the responses (9/11=81.8%) indicated that assistance was provided by a companion. One participant mentioned having sought assistance from an employee of the shop where the display was located, and another participant reported assistance from a passer-by. Four of our participants (36.4%) mentioned not needing assistance when interacting with some public displays, but two of them also selected the option *assistance-from-companion* to refer to interactions with other displays. Pairwise comparisons (FDR method used for p -value adjustment) revealed significant differences between *assistance-from-companion* and *assistance-from-passerby* ($p<.05$), *assistance-from-companion* and *assistance-from-employee* ($p<.05$), and *assistance-from-companion* and *assistance-unavailable* ($p<.05$), respectively.

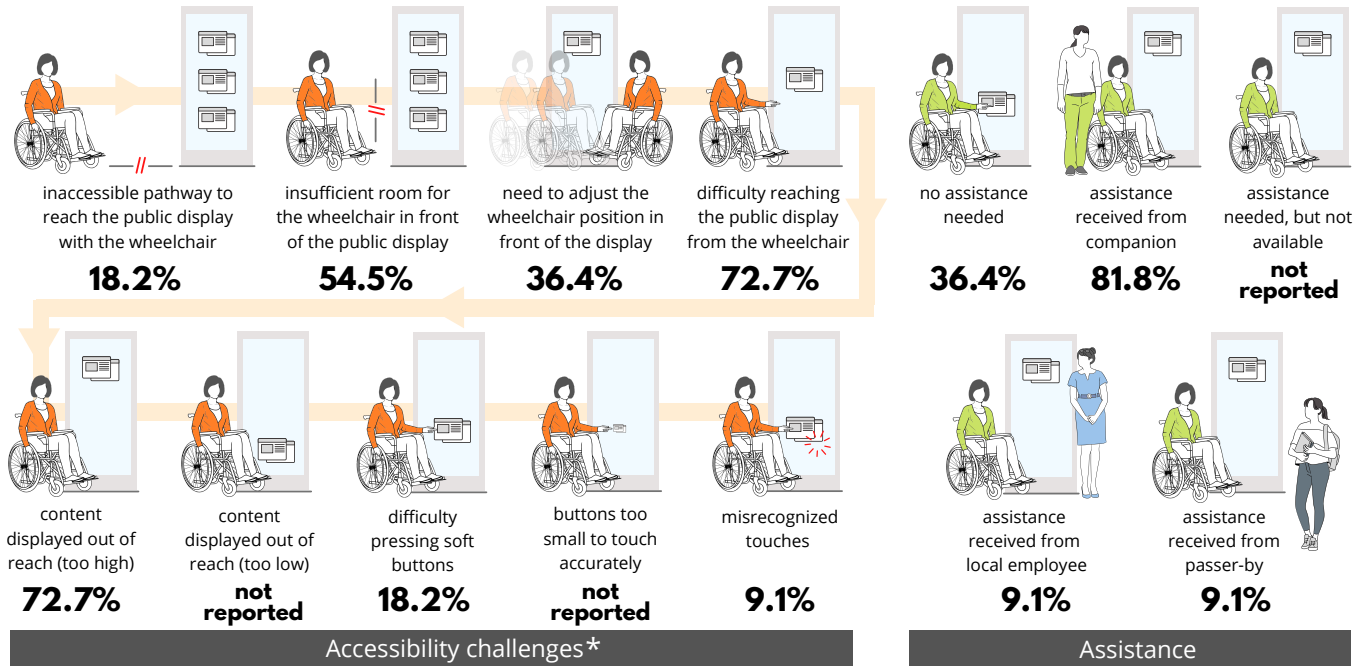
5.5.3 Perceived usefulness of input modalities alternative to touch.

We asked participants to express their preferences for input modalities alternative to touch. The highest preference was for *cast-to-smartphone* ($Mdn=5, M=4.4, SD=1$), followed by a *smartphone-app* ($Mdn=4, M=4.1, SD=0.9$), and *smartphone-as-a-mouse* ($Mdn=4, M=3.9, SD=1.3$); see Figure 5. The other input modalities scored lower ($Mdn\leq 3, M\leq 2.6$), below the Likert-scale item corresponding to “moderately useful.” A Friedman ANOVA revealed a statistically significant effect of INPUT-MODALITY on participants’ ratings ($\chi^2_{(8)}=37.517, p<.001$). Post-hoc Wilcoxon signed-rank tests (with p -value adjustment) did not detect any statistically significant difference between the top-3 most preferred input modalities. We detected several statistically significant correlations between participants’ preferences for INPUT-MODALITY and their disability levels; see Figure 5, bottom. The level of disability correlated highly and positively with preference ratings for *wheelchair-as-a-mouse* ($\rho>.850$), *eye-gaze* ($\rho>.700$), and *head-gestures* ($\rho>.800$), and negatively with *wheelchair-as-a-mouse* ($\rho = -.818$ for WHODAS-2.0). These findings show that while consensus was more easily formed for the top-3 most and also top-3 least preferred input modalities, preferences for the rest of the input modalities varied according to specific motor symptoms. The histograms from Figure 5, middle show ratings ranging from 1 (“not useful”) to 5 (“very useful”) for *wheelchair-joystick*, *wheelchair-as-a-mouse*, and *speech*, suggesting the need for an ability-based design [91] approach. We resume this aspect under Section 6. Two participants (P_6 and P_9) suggested other input solutions they believed could work for them, where the smartphone is used for selecting options from the display by reading QR codes, e.g., when ordering from a restaurant, the display shows QR codes next to each item from the menu; see Figure 6f.

5.6 Qualitative Findings

Although we did not receive many free-form comments, the few ones that we obtained are useful to complete our quantitative analysis from the previous subsection and provide further insights into our participants’ experiences with public displays; see Figure 6.

Participants’ comments were about their personal experiences with specific public displays. For instance, P_2 said “I have never had problems using the display from the restaurant or the highway. However, I remember one display from a local fair when, because of sun glare, I was not able to see anything from my wheelchair.



*Our illustrations depict wheelchair users since they were mentioned the most in the sources analyzed in our SLR (100%) and SVR (83.3%) studies.

Figure 4: Left: The conditions of the ACCESSIBILITY-CHALLENGE variable illustrate, from top to bottom and left to right, potential challenges from navigating towards the public display to touching its screen. Right: Types of ASSISTANCE to which our participants reported having resorted during their interactions with public displays.

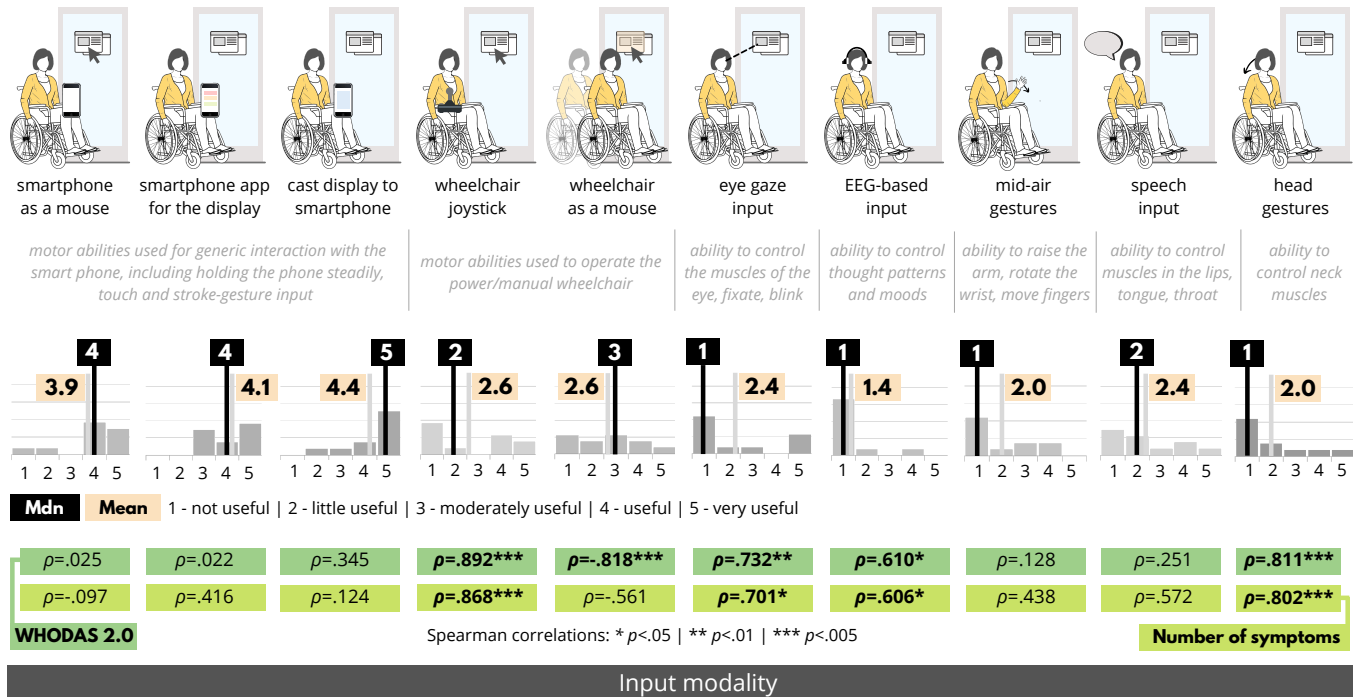


Figure 5: Top: Illustrations of input modalities alternative to touch input for interactive public displays and corresponding motor abilities to use them. Bottom: Correlations between participants' preferences for input modalities and their health conditions evaluated with WHODAS 2.0 scores and the number of self-reported motor symptoms.

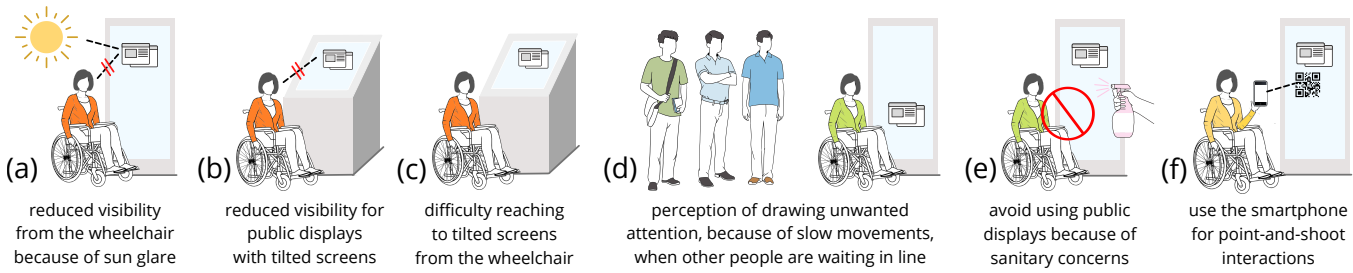


Figure 6: Accessibility challenges (a-c), perceptions of interacting in public places (d,e), and a new input technique that uses the smartphone (f) that resulted from participants’ free-form comments during our semi-structured interviews study.

People standing up did not have this problem. A handle to hold on to and lift my body a little would have been very helpful at that point.” Sun glare was also mentioned by P₈: “The public display from the central square where you can see the highlights of the city, the events, the schedule of the institutions, is always in direct sunlight”; see Figures 6a and 6b. P₅ reported: “Even ATMs are difficult to use. They are designed so that people bend over their screen for privacy reasons. But you hardly can use them from the wheelchair. For now, I can lift myself up to look at and touch the screen, but I don’t know for how long I will still be able to do that” (Figure 6c).

Some participants provided details about their specific motor impairments and the impact those impairments have on interactions with the public display. For example, P₅ said: “Because my movements are slow, sometimes the display changes content before I get the chance to make my selection, so I need to start over—and not just once.” Taking a longer time to interact with the display was mentioned by P₇ and P₈ as well. For example, P₇ witnessed “I feel like I’m making the others who follow me in line wait too much. Sometimes, I feel they want to tell me to hurry, decide faster, make my selection [at the restaurant] faster,” and P₈ said “The public displays from the town hall and hospital, I think it would be useful to have an application that I can try out from home, so that I would already know how to use it without wasting time on the spot and without making people wait for me” (Figure 6d). These comments corroborate our quantitative result regarding a high UNWANTED-ATTENTION rating. Such perceptions lead to giving up using public displays entirely, e.g., P₈ “I am always afraid not to do something wrong or to push a button that is the wrong choice,” and P₁₁ “I know I can’t reach the buttons on the screen, so I avoid using public displays. I prefer to avoid situations that put me in an embarrassing position.” Besides accessibility challenges and social aspects of interacting with displays in public places, sanitary concerns [48] can lead to avoiding using public displays, e.g., P₇ said “Since the COVID pandemic, I have been reluctant to use public displays. I know the displays are easy to disinfect, but that doesn’t happen after each and every person” (Figure 6e).

5.7 Takeaways

Our interviews confirmed interactive content located too high on the display as a major accessibility challenge. We also collected information about types of assistance, and found a high preference for smartphone-based solutions to mitigate accessibility challenges

towards independent use of interactive public displays when assistance is not available. In the next section, we capitalize on the findings from all our three studies to discuss two implications for more accessible interactive public displays.

6 DISCUSSION

Our SLR study revealed very few academic publications on interactive public displays and wheelchair users. This finding contrasts the large body of accessibility research conducted for users with motor and mobility impairments and other interactive systems, including desktop computers [24,26,63,72], mobile devices [2,33,39,54,55,59,82], and wearables [50,77,81], which have received significant attention. Our SVR study revealed users’ perceptions of accessibility challenges during interactions with public displays, but also several input modalities alternative to direct touch. Finally, our interviews with eleven wheelchair users enabled us to elicit preference ratings for a variety of input modalities and understand the need for assistance during interactions with public displays. In this section, we capitalize on these findings to propose two implications: (i) an extension of Vogel and Balakrishnan’s [87] four-phase interaction model with a public ambient display with the “assisted interaction” phase, and (ii) an extension of Brudy *et al.*’s [11] taxonomy of cross-device design with the “ability” dimension to support independent use of public displays via smartphone-based input. We also discuss applications of our findings for other users of public displays.

6.1 The Assisted Interaction Phase

Our findings revealed the importance of assistance during interaction with public displays that are little or not accessible. The presence of an assistant means that two people interact with the public display to perform the same task, which depicts a use case not covered by Vogel and Balakrishnan’s [87] four-phase model, i.e., *ambient display*, *implicit*, *subtle*, and *personal interaction* phases; see Figure 7, left for an illustration adapted from [87, p. 139]. The predominant input modality for public displays is direct touch, as revealed by our studies, but touch-based interactions in the personal zone can be difficult for wheelchair users. In such cases, assistance is provided by other people, e.g., a companion, an employee from the location where the display is installed, or a passer-by, who also become users of the public display. We call this fifth phase *assisted interaction*; see an illustration in Figure 7, right. The transition to the assisted interaction phase can occur from subtle interaction when the users know that the display is not accessible from their

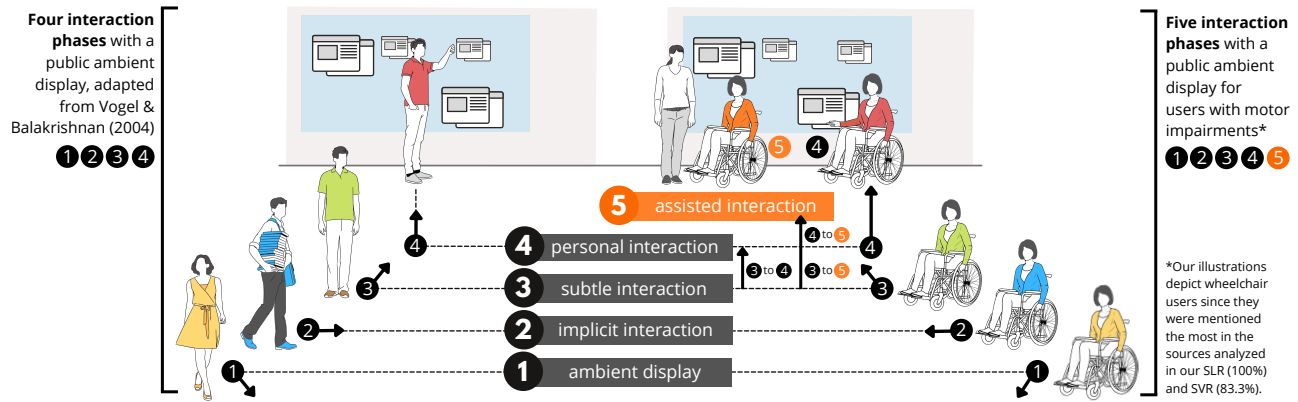


Figure 7: Five interaction phases for public displays (right), adapted from Vogel and Balakrishnan’s [87] four-phase model (left).

prior experiences with it, or from subtle to personal to assisted interaction, a process that allows multiple levels of assistance, as discussed next. However, assistance is not necessarily the endpoint of our model. For wheelchair users that interact with the display independently, transitions stop at the personal interaction phase, as indicated by the arrows from Figure 7, right. However, the *assisted interaction* phase presents unique characteristics; see next.

6.1.1 Two users, one task. The secondary user that provides assistance to the primary, wheelchair user can participate in the interaction with the public display at various levels of engagement. For example, they can help with a single operation, e.g., pressing a button located too high to reach comfortably from the wheelchair, after which the primary user resumes the interaction, i.e., *one-time assistance*. Or, the secondary user can continue from the point where the primary user left off, i.e., *continuation*. The secondary user can also perform the entire task from the beginning, i.e., *full assistance*. These nuances in how assistance is provided have implications for the technical design of public displays that adapt to their users by observing the interaction [31,64,65] or that employ users’ preferences/profiles to customize subsequent interactions [16,83]. For example, a display that has already adapted its interface to the primary user’s height [64] or touch accuracy [31] may be confused by the input characteristics of the secondary user during *one-time assistance* and *continuation*. Although multi-user interaction has been examined for large displays [41,52,61,74,87], this prior work has not addressed simultaneous adaptation to multiple users’ abilities. Examination of multi-user interaction scenarios with the same touchscreen display, where the users have different motor and mobility abilities that enable them to navigate to and reach the display as well as to view and touch the information presented on the display will lead to advances in public display UI technology. These include adaptive multitouch gesture recognition techniques, e.g., based on [56], that leverage multiple users’ abilities to touch the screen in personalized ways, but also creation of new design knowledge for collaborative UIs for interactive public displays [34], where the collaboration subsumes an assistance component.

6.1.2 Interactions between users. Besides the interaction with the public display, human-human interactions take place during the *assisted interaction* phase. For example, the secondary user may need specific information from the primary user to enter in the application running on the public display during *continuation* and *full assistance*. The dialogue between the two users needs to be filtered out by displays implementing speech input [15,57,68]. A potential technical solution may be fusion of information extracted from recognized speech, e.g., to infer whether the interlocutor is the interactive system or another user, with understanding the body behavior of the two users, e.g., synchronized speech with head movement and head orientation towards the other user rather than to the public display. Regarding the latter, interactive displays that track the user’s head [60,68] or eye gaze [40,96] movements may get confused (e.g., they could pause the interaction) by orientations of the user’s head not aimed at the display. Adaptive head- and eye-gaze-based interaction techniques that are tolerant to user attention that momentarily switches towards other, multiple human interlocutors are needed and interesting to explore for such interactive contexts. These aspects make the *assisted interaction* phase a three-way interaction process with two human users, one public ambient display, and multiple attention switching possibilities to individual two-way interactions, which must be modeled accordingly during design.

6.1.3 Privacy aspects. There are obvious privacy and security aspects when assistance is sought from a stranger for interactions that involve confidential or sensible information, which makes implementing the *assisted interaction* phase technically challenging. Potential technical solutions may involve distributed user interfaces [23,53] with the confidential information entered by the wheelchair user on their personal mobile or wearable device, from where it is securely transferred to the application running on the public display. Such solutions also require attention to technical aspects about implementing secure data communications between the user’s personal devices and the public display [43]. Privacy may also be a problem when the assistant is not a stranger, but

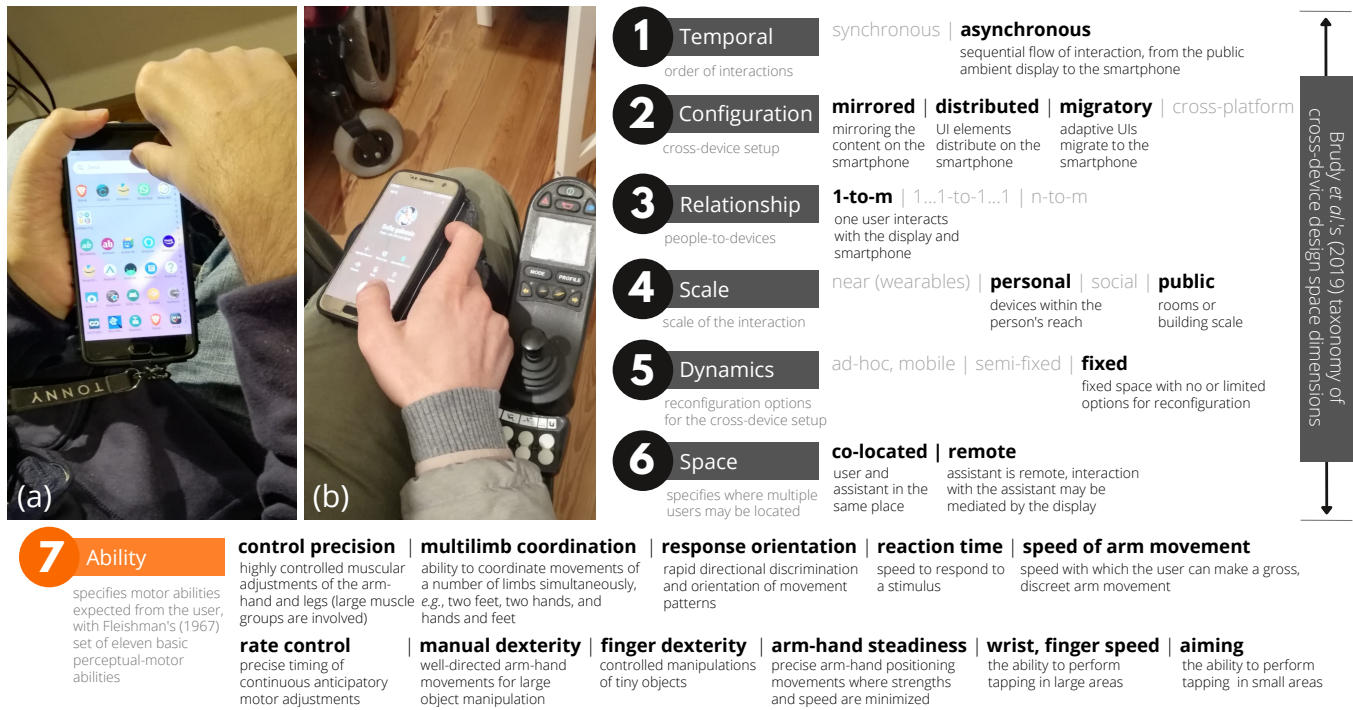


Figure 8: Top left: Successful smartphone use from the wheelchair by a person with Spinal Cord Injury (a) and a person with Traumatic Brain Injury (b). Right: Characterization of smartphone-based interaction with public displays using Brudy et al.'s [11] taxonomy of cross-device design dimensions. Bottom: The seventh dimension of “ability” that we propose to complement Brudy et al.'s [11] taxonomy with a set of basic motor abilities needed to operate mobile devices.

a trusted companion, if someone else eavesdrops on the dialogue between the two users, i.e., a shoulder-surfing situation [12,22] that may open the opportunity to steal information. Methods for protecting information in shoulder-surfing situations, such as those described in Brudy et al. [12], become imperative for public displays supporting the *assisted interaction* phase.

6.2 Cross-Device Interaction Involving the Public Display and the Smartphone

The previous section proposed the *assisted interaction* phase to address, by design, those situations where touch input with the public display is little or not accessible to wheelchair users. However, independent use of the display can be accommodated by alternative input modalities to direct touch. The findings from our interviews revealed a high preference for smartphone-based technical solutions to interact with a public display, which could mitigate many of the accessibility challenges of navigating to the display, raising the hand to reach the display, and touching its screen. Even when mobile devices are not specifically designed to be accessible, prior work has shown that people with motor impairments develop coping strategies and workarounds that enable them to use such devices effectively. Figures 8a and 8b show two examples of smartphone use from the wheelchair provided by two of the participants from our interviews study. In the first example, a person with tetraplegia caused by Spinal Cord Injury employs hand poses characteristic to the development of “functional hands” [21],

which enable him to use the smartphone effectively despite the lack of control of the wrist and finger movements. In the second example, a person with Traumatic Brain Injury employs a strap to hold the smartphone steadily on his thigh and, thus, to increase the accuracy of touch input. Other examples are available in the scientific literature [39,54,59,85]. In this context, reusing personal mobile devices for interactions with public displays represents a convenient approach to support independent use of public displays.

Such an approach falls in the area of cross-device interaction [11] since it involves a personal device and the public display. From the perspective of cross-device interaction design [11], smartphone-based solutions for public displays can be characterized as asynchronous, a 1-to-m relationship between one user and multiple devices, performed both at the personal and public scale, with a fixed dynamics, and implementable in a variety of configuration setups; see Figure 8, top right for an illustration of Brudy et al.'s [11] six-dimensional taxonomy of cross-device design, which we applied to smartphone-based interaction with a public display.¹²

Although using smartphones to interact with public displays has been largely addressed in the scientific literature [3,16,17,36,42,62], interaction techniques have targeted the “average user” (see our discussion of the “average user” in Section 1), while implications for users with motor and mobility impairments have not been covered. This aspect becomes evident when looking at the nature of the six dimensions of cross-device design [11]. Although these

¹²The taxonomy can also be used to accommodate an assistant on the *space* dimension.

dimensions are useful to inform smartphone-to-public-display interactions, they do not consider users' specific abilities to employ mobile devices, e.g., the smartphone in our case. Thus, they offer just a partial view on the design challenge for users not possessing "average," but specific motor abilities. To complete this design space, we turn to ability-based design [90,91], an approach to designing accessible interfaces that are general, yet flexible to address a range of users, but also interfaces that are personalized to specific user groups or individual users. In this context, we propose a seventh dimension to complement Brudy *et al.*'s [11] taxonomy, which we call "Ability"; see Figure 8, bottom. This dimension specifies motor abilities that are expected from the user during cross-device interaction involving a mobile device and the public display. For smartphone-based input, it specifies abilities required to operate a smartphone, to which we already hinted in Figure 5, e.g., motor abilities needed to hold the smartphone steadily during operation, touch targets accurately on its screen, slide the finger across the screen to perform swipe gestures, etc. Also, different motor abilities are needed to implement different types of cross-device interactions, e.g., for controlling a cursor on the public display [4] or holding the smartphone in front of the body to capture head gaze [5].

To operationalize the Ability dimension for practical applications, a set of motor abilities is needed. To this end, we suggest using the taxonomy of perceptual-motor abilities proposed by Fleishman [25], which has been key in motor learning, motor control, and individual differences psychology; see an in-depth discussion in Magill and Anderson [46]. Fleishman's objective was to describe motor skills in terms of general ability requirements in order to account for human performance on a wide range of tasks with a relatively small number of abilities and, consequently, is also useful in our case. These basic motor abilities are enumerated in Figure 8, bottom. Although generic to be applied to a variety of tasks and to describe a diversity of perceptual-motor skills, the use of these basic abilities in the cross-device interaction context makes them informative for designers to propose accessible interactions with public displays via the smartphone. For instance, *manual dexterity* represents the ability to perform well-directed arm-hand movements needed to manipulate the smartphone and hold it steadily, such as for the design solution suggested by one of the participants from our interviews study, who proposed to point the smartphone to QR codes from the public display to select specific options (Figure 6f). *Multilimb coordination* represents the ability to use both hands simultaneously, such as for a more stable grip of the smartphone (as shown in Figure 8a). *Aiming* is the ability to perform accurate tapping on a surface, e.g., to select targets on the smartphone's touchscreen. *Control precision* denotes fine, highly controlled, but not overcontrolled muscular adjustments of the arm-hand and leg movements where the large muscle groups are involved, characterizing smartphone use with different body parts [33].

It is not our goal to conduct an exhaustive examination of this dimension, for which we leave the investigation of direct application opportunities and corresponding technical solutions for future work. For example, the specific motor abilities of the user, stored in the form of a user profile on their smartphone, could be uploaded to the public display and used for the adaptive migration of the UI from the public display to the smartphone across the Configuration dimension of the cross-device design taxonomy from Figure 8, right.

Also, users' preferences for interactions could equally be uploaded to the public display as part of the same user profile, such as the personalized gesture sets from the nomadic gestures technique [83]. We note the complementarity provided by Ability to the other dimensions of Brudy *et al.*'s [11] taxonomy by acknowledging, as part of the design process, users' different motor abilities needed for effective cross-device interactions. In the juxtaposition of the dichotomies public-personal and direct-indirect interaction, the Ability dimension is useful to specify the motor abilities that make wheelchair users choose personal and indirect (via the smartphone) over public and direct (via the public display) interaction.

6.3 Other Applications and Future Work

Our findings have other applications and can inspire future work in other areas. For example, the *assisted interaction* phase for public displays will likely apply to other user categories, such as users with visual impairments, or children who, due to their short stature, cannot reach interactive content located too high on the display. Explorations of accessibility challenges for such user categories may also lead to nuances in how interactions are performed during the *assisted interaction* phase, which we leave for future work as well. Also, our findings indicated the smartphone as the preferred mobile device for public display interactions, but the proliferation of wearables, such as smartwatches,¹³ may lead to other opportunities for implementing interactions with a public ambient display, especially when wearables are designed to be accessible [49,81,86]. Such explorations are interesting to consider in future work, given the convenient characteristics of wearables for conditions of motor impairments: their always-availability, no need to hold steadily during use, take out, or store away compared to the smartphone. The accessibility of content located too low on the public display may represent a challenge for wall displays that feature specific input modalities, e.g., foot tapping and gestures [37,89]. While foot-based input may not be possible for all people with motor disabilities, accessing content from the lower part of the display with the hand by wheelchair users with paraplegia may be feasible. Thus, a part of the display that is more difficult to reach for a user without motor impairments [37] could be leveraged for accessible interactions for wheelchair users. We leave such explorations for future work.

7 LIMITATIONS

In Section 3, we focused our examination of the scientific literature on interactive public displays for people with motor and mobility impairments that are also wheelchair users, according to the specific search keywords that we employed in our SLR. Although our queries from the SVR study were broader in scope, our implications from this paper are limited to wheelchair users. Conducting another SLR with other keywords denoting specific motor impairments may lead to new results. Nevertheless, we expect these results to be limited. For example, a similar query to the one that we used in our SLR, but with the keyword "muscular dystrophy" instead of "wheelchair," led to eight records returned by the ACM DL, and another with "walking aid*" instead of "wheelchair" to two records only, of which

¹³ According to a January 2020 Pew Research Center Report, one-in-five Americans use a smartwatch or fitness tracker, <https://www.pewresearch.org/fact-tank/2020/01/09/about-one-in-five-americans-use-a-smart-watch-or-fitness-tracker>.

we found either papers not relevant to our scope or already included in our SLR focused on wheelchair users. The limited scientific literature on interactive public displays and specific user categories represents a motivation for future work in this direction.

8 CONCLUSION

We conducted three studies to understand accessible interactions with public displays for wheelchair users. Our findings revealed very few scientific publications on this topic, but we identified a diversity of accessibility challenges and opportunities to implement input modalities alternative to direct touch, which should be examined closely in future work. To support such future investigations, we proposed implications regarding a new interaction phase for public displays to address, by design, situations where assistance is needed, and a new design dimension for cross-device interactions to support independent use of public displays via the user's personal mobile device with a focus on users' specific motor abilities.

ACKNOWLEDGMENTS

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI-UEFISCDI, project number PN-III-P4-ID-PCE-2020-0434 (PCE29/2021), within PNCDI III.

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