Accessibility in Context: Understanding the Truly Mobile Experience of Smartphone Users with Motor Impairments

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ABSTRACT
Lab-based studies on touchscreen use by people with motor impairments have identified both positive and negative impacts on accessibility. Little work, however, has moved beyond the lab to investigate the truly *mobile* experiences of users with motor impairments. We conducted two studies to investigate how smartphones are being used on a daily basis, what activities they enable, and what contextual challenges users are encountering. The first study was a small online survey with 16 respondents. The second study was much more in depth, including an initial interview, two weeks of diary entries, and a 3-hour contextual session that included neighborhood activities. Four expert smartphone users participated in the second study and we used a case study approach for analysis. Our findings highlight the ways in which smartphones are enabling everyday activities for people with motor impairments, particularly in overcoming physical accessibility challenges in the real world and supporting writing and reading. We also identified important situational impairments, such as the inability to retrieve the phone while in transit, and confirmed many lab-based findings in the real-world setting. We present design implications and directions for future work.

Categories and Subject Descriptors
K.4.2 [Computers and society]: Social issues—*assistive technologies for persons with disabilities*

General Terms
Design, Human Factors.

Keywords
Accessibility; mobile; assistive devices; smartphones; contextual interviews; case study.

1. INTRODUCTION
The vast majority of research on mobile accessibility for people with motor impairments has focused on controlled lab settings. These studies have shown, for example, that users with motor impairments make more errors than users without impairments [9], are slower, and—for users with *gross* motor impairments—exhibit longer dwell times [14]. Another common challenge is the difficulty of multitouch gestures [14,24]. Early solutions with PDAs and styli employed the raised bezel of the device or a physical overlay to guide the user's input [10,26], physical features that are not available on today's smartphones. More recent recommendations highlight specific target sizes for users with quadriplegia (12mm) [13], and the utility of sliding rather than tapping to reduce input errors for users with tremor [25].

(a) **(b)**

Figure 1. Two study participants in the contextual sessions: (a) phone is hanging by a lanyard around the neck, and (b) phone is on the lap.

Yet, little is known about the *truly mobile* experiences of smartphone and tablet users with motor impairments: How are such devices being integrated on a daily basis into activities such as communication, transit, and shopping? What challenges arise in a mobile context that affect how devices are being adopted, such as the ability to use a smartphone in a busy café or on the street? What activities have smartphones enabled that were previously difficult or even impossible? Perhaps the closest study to answering these questions comes from Kane *et al.* [15], who conducted an interview and diary study on the use of mobile devices that included eight participants with motor impairments; however, smartphones had only recently emerged and only one motor-impaired participant owned one. Their findings highlight the accessibility challenges of mobile devices (largely pre-smartphone), the impact of mobile devices on independence, and the general importance of making mainstream devices accessible. While Anthony *et al.*'s [1] more recent observational study of YouTube videos provides some insight into smartphone and tablet use by people with motor impairments, only 2% of their data included a context outside of the home, school, work, or hospital.

In this paper, we investigate smartphone use by people with motor impairments in a mobile context, primarily outside of the home, through an online survey with 16 participants and multi-method case studies with four expert smartphone users (Figure 1). Both the survey and the case studies compared use of smartphones *in* versus *out* of the home, the activities that smartphones enable, and the accessibility challenges participants encounter. The case studies further included three components: a 30-minute initial interview, a two-week diary study, and, finally, a three-hour contextual session that included neighborhood activities during which participants used the phone.

The contributions of this paper include: (1) Characterizing how smartphones are enabling everyday activities for people with motor impairments, particularly in overcoming physical accessibility challenges in the real world, and supporting writing

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and reading. (2) Extending work on situational impairments and people with disabilities [15] to more explicitly address the needs of people with motor impairments—for example, the at times extreme difficulty of retrieving the phone while in transit. (3) Confirming the real-world impact of challenges previously documented in the lab (*e.g.* [24]), particularly in acquiring small targets and inputting and correcting text. Finally, we present design implications and directions for future work. These results should be of interest to mobile application designers and accessibility researchers who wish to enhance future mobile computing for motor-impaired users.

2. RELATED WORK

We cover studies of mobile adoption and touchscreen interaction for users with motor impairments, and general findings on mobile adoption and situational impairments.

2.1 Accessibility of Touchscreen Input

Mobile devices can increase independence [15] and a sense of empowerment [1] for users with motor impairments. Anthony *et al.* [1] analyzed how users with physical disabilities operate and adapt mobile devices such as tablets and smartphones, finding that, despite challenges, many users were able to use mainstream touchscreen devices and considered them to be empowering. Touchscreen input also offers the advantage that it requires less strength to use compared to physical buttons [12]. At the same time, many basic touchscreen interactions have proven difficult or in some cases impossible [1,3,9,10,14,16,24,25] For instance, Guerreiro *et al.* [13] measured the accuracy of tapping, crossing, exiting and directional gesturing operations with users with tetraplegia, finding that targets located at the bottom of the screen and next to the preferred hand were the easiest to select. As for multi-touch gestures, Trewin *et al.* [24] found that users with motor impairments encountered difficulties in pinching and performing three-finger slides (confirming [1]). Finally, for some users with motor impairments touchscreens are not just difficult but impossible to use [3]. While our research focuses on more holistic questions of mobile device use and adoption, we confirm and extend several of these basic input findings outside of the lab.

2.2 Use and Adoption of Mobile Devices

While not in the context of accessibility, many studies have focused on mobile device use and information needs, including diary studies similar to our own (*e.g.* [5,20,23]). Sohn *et al.* [23], for example, found that the context of use significantly influences mobile information needs and that less essential needs are often put off until later. More closely related to our work is a study by Kane *et al*. [15] that included interviews and a week of diary entries by people with visual and motor impairments. Their design recommendations included the need to support accessibility of mainstream devices, the importance of configurability, and the potential for contextual adaptation; however, as mentioned in the Introduction, only one of the eight motor-impaired participants used a smartphone, which are today widely adopted and are the focus of our study. Moreover, we complement the diary and interview methods with a survey and *in situ* observations to provide a richer characterization of problems encountered in mobile settings. Our focus on mainstream mobile devices is also inspired by Shinohara and Wobbrock's work on stigma [22].

2.3 Situational Impairments

Situational impairments brought on by contextual factors can affect how users interact with a device, such as lighting, glare, noise, rain, weather [21]. These factors are particularly relevant with mobile computing. Research with users *without* motor impairments has shown that input is particularly challenging when the user is in motion, reducing input speed and increasing errors [11,16,17,18,28]. Mobile devices can also impact the user's ability to read information, with motion affecting text legibility [14] and reading comprehension [2]. For users *with* visual and motor impairments, Kane *et al.* [15] identified crowded spaces, lighting and weather, walking, and interruptions as contextual factors impacting mobile device use; however, the findings emphasized experiences of visually impaired participants, with only one explicit reference to a motor-impaired participant (blocking the sidewalk with the wheelchair when stopping to use the device). Our case studies and online survey expand on these findings by explicitly investigating situational impairments encountered by motor-impaired users.

3. ONLINE SURVEY

To compare mobile phone use trends inside versus outside of the home (*i.e.*, when mobile), we conducted an online survey with 16 users with motor impairments.

3.1 Method

Mobile phone users with motor impairments were recruited through distribution lists, online forums, local organizations, Facebook and Twitter; as remuneration, participants could opt into a drawing for a $100 Amazon gift certificate. The survey was designed to take up to 25 minutes and included 26 open- and close-form questions. Questions covered general background (*e.g.*, age, gender, motor impairments), type of mobile device owned, challenges found with basic touchscreen operations (*e.g.*, text input/correction, multitouch gestures), and a comparison of device use, physical setup and challenges encountered in use at home versus around town. For these lattermost questions, we randomized whether at-home or around town was presented first.

Forty complete surveys were submitted worldwide and 23 more were partially completed. Because of regional differences, only surveys from the US were considered (31); surveys that did not indicate motor impairments or that did not include touchscreen experience were further excluded. For the 16 remaining surveys, the average completion time was 15.7 minutes (SD = 8.6).

3.2 Participants

Of the 16 participants, 15 owned a smartphone and one owned only a tablet. Eleven were female, and the median age range of all participants was 35–44. Respondents reported a range of diagnosed medical conditions, including cerebral palsy (8), neuropathy (4), arthritis (4), and spinal cord injury (4), and one each for muscular dystrophy, spina bifida, multiple sclerosis, and spinal muscular atrophy (note: some participants reported more than one condition). Nine participants indicated often using a wheelchair and three did so only occasionally. In addition to motor impairments, seven participants reported speech impairments, six hearing impairments, and three visual impairments. The majority reported that their motor impairment affects their use of the device either substantially (6) or to some degree (3); the remaining 7 reported very little or no impact. Of the 15 smartphone owners, most were iPhone (8) or Android (6) owners, with one Windows Phone owner, and all but two participants used their phones at least once every few hours. Among accessibility tools adopted, nine participants used speech-to-text and one used a screenreader.

3.3 Findings

Participants used their mobile devices in a variety of locations, most commonly the home (15), but also the street, car, or public

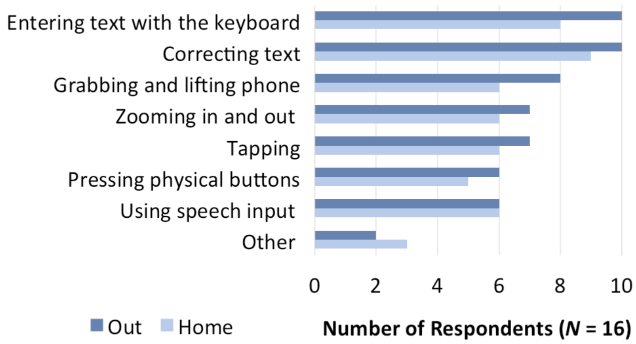

Figure 2. Number of survey respondents citing each input difficulty when using the phone at home versus out (*N* = 16).

transit, among others (at least 8 participants each). To get a sense of how situational impairments impact input, Figure 2 shows the relative difficulties of completing basic input tasks at home versus out. While the overall trends are similar for both contexts (*e.g.*, text entry and correction were most frequently cited as difficult), more participants reported difficulty while out than at home for all but speech input and "other". Physical position of the phone was also different in the two contexts. At home, the most commonly used positions were flat on a table (7) or lap (5), but these locations were reversed when out, where the lap was most preferred (7), followed by table (3).

In terms of application use at home versus out, participants used a wide range of applications in both contexts, such as email, SMS, games, online shopping, and personal organization tools. Similar patterns of use were found for both contexts, except for navigation and personal organization apps, which were more common when out—7 participants used while at home *vs.* 11 while out.

Although not focused on use at home versus out, we asked about three common input difficulties in general: multitouch gestures, text entry, and text correction. On a 5-point scale from very easy to very difficult, 7 out of 16 participants rated multitouch gestures as difficult or very difficult, while 7 and 10 rated text entry and correction, respectively, as difficult or very difficult.

In summary, these results provide some evidence that using the phone outside of the home increases input difficulties for people with motor impairments, a theme that we explore further in the case studies. As well, about half of the participants found text entry and multitouch difficult, which confirms past work [1,24] and highlights the need for more research in these areas to develop accessible solutions.

4. MULTI-CASE STUDY METHOD

To more deeply investigate how smartphones are used by people with motor impairments and the challenges encountered therein, we conducted a multi-case study with four expert smartphone users. The study included an initial interview, two weeks of diary entries, and a 3-hour contextual session.

4.1 Participant Recruitment

Four participants with motor impairments were recruited from Maryland, DC, and Northern Virginia from October to December 2013. We advertised the study through e-mail lists and social networks, at local events and organizations, and through direct contact. To qualify as an expert smartphone user, participants were required to have at least 18 months of smartphone experience and to use the device more than twice a week. All participants were male, aged 24–46; more details can be found in the cases themselves (Section 5). Compensation was provided.

4.2 Procedure

The study procedure consisted of three parts: an initial interview, a two-week diary study, and a three-hour contextual session.

Initial interview. The 30-minute structured interview collected information on demographics, diagnosed medical conditions, smartphone model used, frequency of smartphone use, and assistive technologies used. Interviews were conducted via phone and were audio recorded. The diary procedure was also explained.

Diary entries. Participants reported on their use of the phone once a day for two weeks: applications used, positive/negative experiences, and challenges encountered. The requirement was to complete at least 10 entries, each of which took about 10 minutes; entries could be completed at most one day late. For accessibility, participants could use a Google Form, email or voicemail, but all chose the Google Form. We sent a reminder at 7PM each day by email, SMS, or voice message, whichever mode was preferred by the participant. The diary form included the following close- and open-ended questions, with the last two questions being optional:

- *For which of the following tasks did you use your phone today?* Set list, such as "Navigation/GPS" and "Email".
- *What activities did you do outside the home today?* Set list, such as "Traveling around town" and "Shopping".
- *For what activities was the phone especially helpful today inside or outside the home?*
- *What are the worst experiences you had with the phone today?*
- *Were there other accessibility issues you encountered today not involving the phone? If so, please explain.*
- *Please share any other comments or ideas you have about your phone experience.*

Contextual session. Finally, a three-hour contextual session was scheduled with each participant. Contrasting the diary entries, this session allowed for interview and observation *in situ*, as participants completed tasks on the go. Sessions took place in public locations (*e.g.*, coffee shop, pharmacy), with the exception of one participant (discussed later). Each session consisted of:

1. *Basic smartphone actions (10 minutes)*. To assess basic smartphone accessibility for each participant, we had them complete ten tasks on a Samsung Exhibit smartphone: pick the phone off a table, long swipe in any direction, horizontal and vertical swipe, short tap on a target (at center, left, and right of screen), long tap, pinch, and drag. Participants performed each action twice and could fail twice before moving on to the next action.
2. *Semi-structured interview and short demos (1.5–2 hours)*. Questions covered general aspects of smartphone adoption, and expanded on points from the diary entries. The latter questions also included demonstrations by the participant of particular use scenarios and accessibility challenges.
3. *Neighborhood activities (up to 1 hour)*. Up to three activities were selected based on the diary entries and in consultation with the participant about regular errands and activities outside of the home (*e.g.*, shopping, public transit). During these activities, participants demonstrated use of the phone.

For the contextual session, audio recording devices were attached to the participant and the researcher during mobile activities. Video was taken of the basic smartphone actions (to capture success/failure) and of short demos. During the neighborhood activities, video and still images were selectively taken. Written notes were taken during and after the session, particularly on physical use of phone.

4.3 Data Analysis

We analyzed the data using a case study approach [7]. The initial interviews and contextual sessions were transcribed, after which the transcripts and diary entries from the in-person sessions were qualitatively coded. We created an initial code set on a first pass of the data, and subsequently grouped codes in a hierarchy. After a second pass to refine the code set, emergent categories were selected for an axial coding analysis. From this process we identified four main themes covering 18 categories (for 80 codes in total). The themes and sample categories were *enablement* (*e.g.*, organization, transport, activities), *challenges* (*e.g.*, situational impairments, physical world, mobile input), *personalization* (*e.g.*, customization, preferences), and *wishes* (*e.g.*, mobile enhancements, physical world control).

The coding process was validated on a subset of the data using peer-review [7] with one external reviewer not on the research team. Six of the 18 categories were reviewed: three randomly selected categories (activities, organization, transport), and the three categories most relevant to our research questions (situational impairments, social acceptance, physical world control). The external reviewer read through all excerpts in these categories, and marked agreement or disagreement about whether the correct code had been applied. Finally, both coders reviewed instances of disagreement.

5. MULTI-CASE STUDY FINDINGS

We first present each case individually, focusing on physical use and the themes of enablement and situational impairments (our primary topics of investigation), followed by a cross-case analysis. For each participant, their smartphone model, physical ability to use the phone, and common information tasks are summarized in an accompanying table.

5.1 Case P1

P1, a male aged 46, has muscular dystrophy and some visual impairment; he uses a wheelchair only occasionally and owns an Android Nexus (Table 1; Figure 3). He completed 14 diary entries over 14 days. During the contextual session, he demonstrated sharing files on Dropbox, checking sports information, reading books, playing games, using SMS with voice control, and using social networks (Facebook). Neighborhood activities included a short walk to a pharmacy and a visit to a subway station.

Enablement. Using a smartphone allows P1 to take care of home activities like meal planning and laundry, to write and read more, and to access information on the go. He prepares meals by using the Kindle app to read recipes in the kitchen, and keeps track of shopping lists, to-dos and calendar entries on the phone:

"Because I have a disability I am not doing the physical work of the house. My job is meals, meals planning. Keeping a calendar straight. It would be more difficult for me to do that without the phone."

While P1 has difficulty with physical writing due to a lack of strength, he can enter text on the touchscreen for notes and other personal organization needs. The phone also allows him to read books and newspapers by enlarging text, reversing colors, or using text-to-voice (*e.g.*, Kindle or Darwin Reader apps). P1 compared the phone to printed text:

"I've already tried very, very hard to read print because there wasn't as much available and now 90%...at least 75% of all books are available in electronic format, so I actually read more now than I read four years ago… just because of the accessibility."

Table 1. Overview of P1's phone use based on diary entries and the basic smartphone actions in the contextual session.

Smartphone: Android Nexus with magnification and text reader.
Primary uses: Communication (email, voice calls, SMS), weather reports, books, calendar and scheduling.
Position of phone: P1 manipulates the phone by holding it with his left hand on his lap. When not in use, he stores the phone in a pocket or attaches it to a neck-worn lanyard by a hook on the case.
Physical ability to use phone (10 basic actions): Grabbing and lifting the phone, and multitouch gestures (pinch) were difficult.
Activities outside of the home: Traveling around town and commuting, work, shopping and groceries, sport and social.

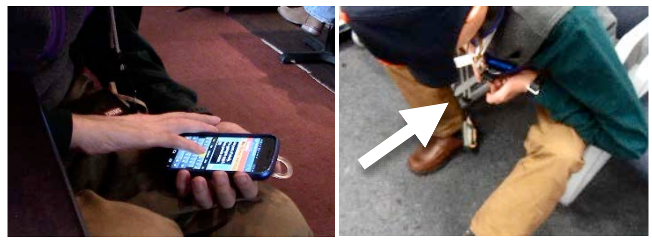

Figure 3. P1 entering text in the phone (left) and moving his phone from the pocket to his lap (right).

Finally, mobile information helps P1 avoid physical challenges while out. For example, subway fare machines are not accessible to him, so he adds fare to his card on the mobile website. He can also check if a business is open before visiting, or perform mobile online payments. Without the phone he commented that he would need to be more cautious in preparing for activities.

Situational impairments. P1 must sit to use the phone, so he tries to complete any necessary mobile tasks before leaving. Because of the considerable effort to take out and store the phone, he typically uses it only on longer public transit rides. Among other factors, weather and clothing impact P1's ability to use the phone:

"When it is warm out I can carry it [the phone] in my shirt pocket and access it. When it is cold I have to carry it in my jacket pocket. I am afraid I will drop it. And, it is more difficult for me to access the mobile phone while wearing a jacket."

Privacy can be an issue with the text-reader mode on the phone, such as when P1 forgets to turn the sound off at work. That said, he prefers having the mode enabled rather than taking his phone out of his pocket, trading off privacy for accessibility.

Other accessibility challenges. P1 finds voice-to-text on his phone so inaccurate compared to Dragon Naturally Speaking on his desktop computer as to not be useful. Text input is also a problem, and he waits until home to compose longer messages.

5.2 Case P2

P2, a male aged 24, has had cerebral palsy since birth, affecting motor control and speech; he uses a wheelchair and owns a Samsung Galaxy S4 (Table 2; Figure 4). He completed eight diary entries over 10 days. During the contextual session he demonstrated use of the phone for personal organization with calendars and emails, web browsing, online shopping, social networks, restaurant coupons, and tourism apps to book hotels. Neighborhood activities included a walk to a mall, a visit to a pharmacy and a visit to a coffee shop.

Enablement. P2 finds the phone especially useful for working remotely because he can work any place and any time: "*I would go in my scooter, reading and working from there, so I would work whenever.*" When he was in college and working, he also sent and responded to work emails on his phone while on campus.

Mobile information also allows P2 to plan or adapt his daily activities when an incident occurs—similar to P1. One diary entry discussed a morning with inclement weather:

"I coordinated with my co-workers and taxi driver to make sure I could safely get to work on my phone before I even got out of bed."

As with P1, P2 finds writing on paper to be difficult, but the phone allows him to write reminders, manage contacts, and use calendars. He makes use of these tools across devices. For instance, he mentioned that when he goes grocery shopping, he takes notes from his iPad at home, emails them, and accesses them from the phone at the store. As he commented:

"I don't write very well. I have always used an online calendar since high school. Now, I have my Outlook connected to my Google calendar, so they are all in sync."

Situational impairments. Weather is the primary contextual factor affecting P2. He prefers to have his phone on his lap (Figure 4, left), which makes rain and snow problematic. During inclement weather he has to protect his phone and thus cannot take it out easily:

"I got caught in freezing rain. I cannot easily use pockets, so I have trouble finding a place to put my phone where it won't get wet."

Other accessibility challenges. While P2 can operate his smartphone as-is, he reported challenges in text correction, copy-paste, multitouch gestures and plugging in the phone. Touchscreen input becomes challenging when he needs to type fast: *"With my tight schedule, trying to hurry and quickly dial into a call is frustrating because I make mistakes."* Text correction is also difficult, particularly because the control to correct a word is so small. For long text input, P2 prefers to use other devices, saying: "*typing a lot on my phone can get difficult so I use my laptop and iPad to type when I can.*"

5.3 Case P3

P3, a 30-year-old male with a spinal cord injury (quadriplegia with poor hand dexterity), completed 13 diary entries over 14 days; he owns an iPhone 5 (Table 3; Figure 5). The contextual session included demonstrations of operating his workstation remotely from the phone, accessing podcasts and videos, using Assistive Touch, and entering text with Siri and the iPhone keyboard. As his diary entries included few activities outside of the home and because P2 lives in a rural area, the session was adjusted to include a driving demonstration and use of GPS for navigation instead of neighborhood activities.

Enablement. One area of enablement for P3 was the support of routine tasks and personal organization at home, for which the phone provides a sort of freedom—for example, being able to create reminders whenever he needs help with housework activities like changing bed sheets. He also uses the phone to pass time during a daily two-hour physical routine:

"Before I had the phone, I used to drag my laptop into the bathroom with me, set it up on my sink and listen to Google videos and things like that. The phone has completely replaced that."

As with P1 and P2, P3 uses his phone to reduce physical effort. With *Pocketcloud* he remotely controls his workstation, allowing him to manage video processing or play music from the bed or couch without having to use his wheelchair to get to his desk.

Situational impairments. While he is out, P3 sometimes has physical difficulty retrieving his phone from his bag. This can make it difficult to answer a call, for which he typically prefers to wait until later: "*I'd just wait until I have a moment where I have some quiet or peace or I can lock my wheelchair.*"

Other accessibility challenges. P3 finds it difficult to select small targets and to complete multitouch gestures. For example, he demonstrated the difficulty of tapping targets and making accidental taps in Assistive Touch. Problems with tapping small

Table 2. Overview of P2's phone use based on diary entries and the basic smartphone actions in the contextual session.

Smartphone: Samsung Galaxy S4 with no assistive technology.
Primary uses: Communication (SMS, social network services, email and voice calls), web browsing, personal organization, and mobile payments.
Position of phone: P2 operates his phone by holding it on a table or with his left hand. When he moves around, the phone is located on his lap or on his scooter table.
Physical ability to use phone (10 basic actions): P2 encountered challenges performing a one-hand multitouch gesture. To zoom in and out he used both hands for the pinch gesture, which requires to the phone to be on a table or other support.
Activities outside of home: Shopping and groceries, travelling around town and commuting, work, and social.

Table 3. Overview of P3's phone use based on diary entries and the basic smartphone actions in the contextual session.

Smartphone: Apple iPhone 5 with no assistive technology.
Primary uses: Entertainment, access to email, access to social networks, web browsing, and reading news and articles.
Position of phone: P3 prefers to hold the phone in his left hand, using a tripod stand on the case to do so in a stable manner (Figure 5). When mobile, he places the phone on his lap or in a bag.
Physical ability to use phone (10 basic actions): For pinch-to-zoom, P3 first tried with the ring and middle fingers on one hand, but had to switch to two hands when that did not work.
Activities outside of home: Visiting family and occasionally dining with friends on weekends.

Figure 4. P2 with his phone on his lap while stationary (left), and showing challenges correcting text (right).

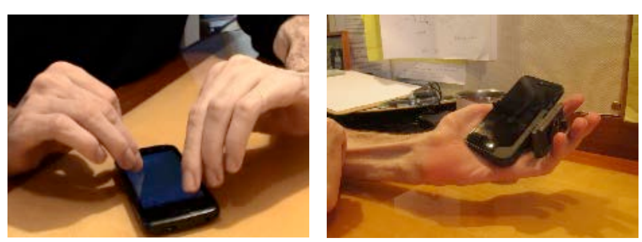

Figure 5. P3's two-handed pinch gesture (left); holding the phone by using the tripod mount on the case (right).

elements also appear when he has to correct text by placing the cursor within a block of text. As for voice-to-text, while P3 uses Siri, he finds it difficult for writing an email because he has to plan in advance exactly what to say to avoid having to correct it: *"I don't think it is natural for me to think out a whole sentence that's grammatically correct."*

5.4 Case P4

P4 is a 29-year-old male with cerebral palsy; he uses a wheelchair and owns an iPhone 5 (Table 4; Figure 6). He completed 14 diary entries over 16 days. During the contextual session he demonstrated use of his phone for checking transit information, using a calendar and email, and social networking. Neighborhood activities included visits to a mall, a pharmacy, and a coffee shop.

Enablement. The smartphone enables P4 to overcome physical world challenges, for example: "*So I mean, having the mobile access just reduces the physical effort so much."* For transit, P4 makes daily use of a mobile application to check the elevator status at subway stations. This app is critical because he can know in advance when the elevators are broken and get off at a different station to avoid delays. P4 also uses GPS navigation and maps for long trips. As he summed up regarding transportation:

"It's being able to anticipate elevator outages, and being able to plan outside your routes on public transit and being able to have weather alerts."

P4 also uses the phone to remotely control his TV and stereo speakers via voice commands, freeing him from having to use standard remote controls. The phone is also another device on which he can do online shopping and payments, which he prefers to in-person shopping—grocery store aisles, for example, can be narrow and difficult to navigate:

"Shopping online enables my independence. Shopping in the physical world, well, let's just say I'm a happy Amazon Prime customer."

The mobile device is also important for P4's work. Often when he can't commute due to inclement weather he works from home. As he reported in his diary: *"With mobile access I don't have to worry about that. I don't need to go to this inaccessible place to get my job done."* He can even work from his couch without necessarily needing to use his laptop.

Table 4. Overview of P4's phone use based on diary entries and the basic smartphone actions in the contextual session.

Smartphone: Apple iPhone 5 with Siri as an assistive technology.
Primary uses: Access to information (weather, web, news and articles), communications (SMS, phone, email and social networks), navigation, and personal organization.
Position of phone: P4 holds his phone in his right hand to use it. When he moves around, he keeps the phone in his pocket or hand.
Physical ability to use phone (10 basic smartphone actions): P4 performed all tasks successfully, although he had to use his right hand to hold the phone for the swipe gesture. He reported that he finds it difficult to select small targets and occasionally uses a stylus for text input due to hand tremors or spasms.
Activities outside of home: Traveling around town and commuting, social, work, leisure and shopping.

Figure 6. P4 in a pharmacy, stretching his arm to get items from an aisle (left); P4 holding the phone for use (right).

Finally, P4 uses notes, reminders and calendars on his phone for personal organization. He uses reminders created with Siri on his phone and synchronized with his calendar and other devices.

Situational impairments. Few situational impairments arose in P4's case. One aspect of context that impacts P4's phone use is privacy, for which reason he doesn't use screenreaders: *"The reason I don't use VoiceOver or whatever, because I mean there's not a lot of privacy there.*"

Other accessibility challenges. P4 finds touchscreen text input and correction challenging and for long emails waits until he can use speech dictation on his desktop. The 20-second dictation window that Siri allows is too short for him and impacts the type of emails he writes on the phone. He also finds small target acquisition difficult, such as selecting small areas in a file list or when correcting text. As another challenge, P4 considers size and weight when acquiring a mobile device because of the difficulty in grabbing and lifting it. For these reasons, he does not use a case or headphones.

5.5 Cross-case Analysis and Summary

Overall, mobile phones were used for a range of activities both inside and outside of the home, as participants found smartphones to be more portable than tablets or laptops. All participants reported some activities traditionally performed on their desktop computers were now being done with the phones—for example, P1's recipes or P3's entertainment. In terms of personalization, our participants had adopted no or few assistive technologies with their phones—including software and cases—confirming Trewin *et al.*'s [24] findings with mobile phone (primarily not smartphone) users with motor impairments. Several factors appeared to impact this low rate of adoption, including the desire to maintain portability (e.g., not adding a bulky case), limitations in some assisitive technologies (e.g., poor speech recognition), and in some cases a general lack of need.

We highlight overarching findings for the themes of enablement, situational impairments, and accessibility challenges; we also briefly discuss participants' wishes for future technologies.

Enablement. Mobile information was particularly important for mitigating physical world accessibility challenges: (1) One example is to support *transit*, where P4 checked the elevator status at subway stations and P1, P2, and P4 frequently used navigation apps, as reported in their diaries. (2) The phones also supported *remote work*, allowing for flexibility and the ability to skip the commute altogether in inclement weather. (3) *Online shopping* and mobile apps for *home banking* were found to be useful for similar reasons (P1, P2, P4); the challenges of on-site shopping were evident in the contextual sessions—navigating through aisles, carrying bags, and waiting for assistance to pay. (4) The phones were used to reduce physical effort by *controlling other devices at home*, such as P3's workstation, and P4's TV and stereo via voice commands. (5) Finally, mobile devices provided an *accessible alternative to physical writing*, allowing participants to use calendars, reminders, notes, and lists.

Situational impairments. By focusing on smartphone use and people with motor impairments specifically, we extend Kane *et al.*'s [29] findings, highlighting challenges due to movement, restrictive clothing, and weather. Most notably, all participants preferred to have their phones easily available (*e.g.*, on the lap), but during inclement weather P1 and P4 stored it in a pocket and P2 and P3 stored it in a bag, making access difficult. Participants also had privacy concerns about using speakers and voice-to-text technology in public, similar to Ye *et al.*'s [27] findings with visually impaired users. However, as opposed to reducing these privacy concerns, the use of external devices such as headphones was a detriment to portability for some participants (P3, P4).

Other accessibility challenges. Despite participants being experienced smartphone users, text input, voice-to-text, and acquisition of small targets were still challenging. Participants preferred to use their desktops or tablets to write lengthy text, which reflects similar findings from non-motor-impaired users [23]. Confirming past findings on the accessibility challenges of multitouch input [1,24], only one participant was able to perform multitouch gestures with one hand during the performance tasks—two participants needed both hands and one used AssistiveTouch. Finally, we found that mobile dictation (notably Siri) was not comparable to desktop software (P1, P3, P4) and that text correction was particularly frustrating (P1, P2, P3, P4).

Wishes for future technologies. Three participants wanted more accurate voice-to-text and voice control. P2 also mentioned the need for alternatives to multitouch (*"no pinching"*). Other suggestions collected were: more accessible social apps to share images, cordless battery charging, and apps for image editing as powerful as on a desktop. P3 envisioned self-driving cars and future mobile devices integrated with our bodies, while P4 proposed to control more household devices remotely (*e.g.*, thermostat, coffee machine) using voice commands on the phone.

6. DISCUSSION

Our findings highlight both the ongoing accessibility challenges of touchscreen smartphones for users with motor impairments and the numerous ways in which these devices can be empowering. Though the sample size was small (N=16), the online survey results offer additional evidence to support these conclusions. We extend Kane *et al.*'s [15] and Anthony *et al.*'s [1] findings that mobile devices can be empowering for users with disabilities by characterizing new ways in which this empowerment occurs. Here, we reflect on design implications and areas for future work.

Physical world accessibility. Participants in the case studies used smartphones to mitigate accessibility challenges in the real world and to reduce physical effort—from transit planning to mobile banking to controlling household devices. Building on these trends, designers of *physical* spaces, such as transit hubs, libraries, and malls, should explicitly consider how mobile services can complement and improve physical accessibility (*e.g.,* real-time accessibility information such as crowdedness or working elevators). Likewise, our findings emphasize the potential benefits of future smarthomes, where the mobile device can control a range of household elements [8,19]. Such alternative access would allow users to select a control modality that works for their abilities, such as controlling the device directly, using the touchscreen, or using voice control.

Mobile text input. Several case study participants found mobile text input or speech dictation to be an accessible alternative to physical writing (*e.g.*, notes, calendars). At the same time, text input was remarked to be inefficient, particularly for text correction, selection and copy-pasting; the survey confirmed these findings. While accessible mobile text input has long been a research focus (*e.g.*, [6,26]), text correction has not been prioritized. To improve the accessibility of mainstream keyboards, designers could increase the size of the selection controls, use a modal approach where entering a correction mode magnifies all text, or provide alternative, indirect controls such as sliders to manipulate the cursor. Improved mobile speech input could also address these issues in contexts where it is socially appropriate.

Situational impairments. Kane *et al.* [15] previously identified situational impairments affecting people with disabilities, but as mentioned in Related Work their focus was primarily on visual impairments. Our findings thus extend an understanding of how contextual factors impact mobile accessibility for people with motor impairments. Most notably, participants encountered serious difficulties in physically retrieving the phone for use while they were in transit. For one participant this was a problem all of the time (his phone hung on a lanyard around his neck), while for others it only became serious with restrictive clothing or in inclement weather when the phone was stowed away. Answering phone calls was also difficult on the go, with some participants choosing to postpone calls.

Potential of wearable devices. To address the situational impairments described above, mobile input could be distributed to other devices, such as small wearables (*e.g.* rings, watches), voice control, and the human body. Such devices would be always available, eliminating the cost of retrieving the device. Accessible wearable input is an emerging area of work (*e.g.*, [4,27]), and we expect to see many new solutions in the next few years.

Lab to real-world accessibility challenges. With the exception of Anthony *et al.*'s [1] study of YouTube videos, past work on touchscreen input for people with motor impairments has largely focused on lab settings. Of course, lab findings derived in controlled settings and from artificial tasks do not necessarily translate to meaningful real-world impacts. Our findings confirm, in particular, that difficulties of tapping on small targets, performing multitouch gestures, and entering text are impacting daily smartphone use even for experienced users. Moreover, by studying use in the real world, we were able to identify further challenges, such as the situational impairments described above.

7. LIMITATIONS

Case study participants were all expert smartphone users, male, 24-56, and US residents. As a result, the findings may not generalize across gender, age, culture, and technology experience. For both studies, all participants could use mobile devices, and we did not collect data from those who have more severe motor impairments. While we used multiple methods across the two studies (survey, interview, diary study, observation), overall limitations of the case studies include the small sample size and the lack of a standardized performance assessment of each user's motor abilities and ability to use the mobile device; to overcome this latter issue to some degree, we included a set of ten basic mobile phone tasks (the outcomes are listed in each participant table). Finally, the survey included only a relatively small number of participants. While it provides some evidence to complement the in-person study, the survey findings are preliminary.

8. CONCLUSION

We conducted two studies, a small online survey (N = 16) and a more in-depth set of case studies with four participants with motor impairments. Participants used the devices frequently and for a range of tasks. Our findings highlight the ways in which smartphones are enabling everyday activities for people with motor impairments, particularly in mitigating accessibility challenges in the physical world and in supporting accessible reading and writing. Documented challenges in touchscreen input persist, emphasizing the need for further work on making basic input accessible. We also identified situational impairments that are especially impactful for users with motor impairments. We predict that wearable devices will be a fruitful direction for addressing these challenges in the future, better supporting truly mobile access for people with motor impairments.

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