

Personalized, Wearable Control of a Head-mounted Display for Users with Upper Body Motor Impairments

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ABSTRACT

Head-mounted displays provide relatively hands-free interaction that could improve mobile computing access for users with motor impairments. To investigate this largely unexplored area, we present two user studies. The first, smaller study evaluated the accessibility of Google Glass, a head-mounted display, with 6 participants. Findings revealed potential benefits of a head-mounted display yet demonstrated the need for alternative means of controlling Glass—3 of the 6 participants could not use it at all. We then conducted a second study with 12 participants to evaluate a potential alternative input mechanism that could allow for accessible control of a head-mounted display: switch-based wearable touchpads that can be affixed to the body or wheelchair. The study assessed input performance with three sizes of touchpad, investigated personalization patterns when participants were asked to place the touchpads on their body or wheelchair, and elicited subjective responses. All 12 participants were able to use the touchpads to control the display, and patterns of touchpad placement point to the value of personalization in providing support for each user's motor abilities.

Author Keywords

Motor impairments; wearables; mobile accessibility.

INTRODUCTION

For users with upper body motor impairments such as tremor, lack of sensation, or spasm, smartphones and other mobile devices can present accessibility challenges [1,15,26,33]. Basic interactions like multi-touch gestures and text entry can be difficult and sometimes impossible to use [1]. Even pulling the phone out of a pocket or bag when in a mobile context can be an accessibility barrier [26].

In contrast, emerging mainstream head-mounted displays such as Google Glass offer new possibilities for accessible computing. Such devices are always available and offer

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Figure 1. Examples of participants' touchpad placement using a set of four customizable touchpads designed to provide accessible control of a head-mounted display.

relatively hands-free interaction, potentially alleviating the manual input challenges of today's smartphones and tablets. Recent work by McNaney *et al.* [25], for example, showed in a field trial with 4 participants with Parkinson's disease that Google Glass provided a sense of independence and security, and that few accessibility issues arose with device interaction. Similarly, Carrington *et al.* [4], conducted participatory design work on input and output opportunities that employ the space around a power wheelchair. Though participants in their study did not use a head-mounted display, several felt that it would be a useful output modality. These studies provide an important first step in demonstrating the potential of head-mounted displays for people with motor impairments. We build on their findings by evaluating the accessibility of Glass with a wider range of users than in [25], and by implementing and evaluating an alternative means of controlling such a display.

This paper investigates the relatively unexplored area of accessible, wearable interaction for users with motor impairments in two ways (Figure 1). First, we conducted a small, exploratory study to assess the accessibility of Google Glass (a head-mounted display) with a diverse set of motor-impaired participants, including those with cerebral palsy, essential and orthostatic tremor, and spinal cord injury. Unlike McNaney *et al.*'s [25] findings for users with Parkinson's disease, our study demonstrates that manual input on the side of the Glass device was difficult or impossible for some participants.

Second, we developed a simple, personalizable interaction approach that employs four switch-based wearable touchpads that can be affixed to the body or wheelchair (Figure 1). The term "wearable" here refers to touchpads attached on body as well as on the wheelchair. These touchpads control what is displayed on Google Glass

without having to reach up and touch the side of the device. We conducted a study with 12 participants with motor impairments to assess: (1) baseline input performance with touchpads of three different sizes (2cm, 4cm, and 8cm in width); (2) preferences and rationale for wearable placement of the touchpads; (3) performance when using these customized locations; and (4) overall response to the approach and comparison with Glass's default interaction. Findings show that all participants could independently use the wearable touchpads, choosing to place them in a variety of locations on their body or wheelchair. Rationale for placement and preferences for touchpad size demonstrate the influence of individual motor abilities and further motivate the utility of personalized input for this context.

The contributions of this paper include: (1) a simple, customizable input solution to allow users with motor impairments to control a head-mounted display via switch-based touchpads; (2) empirical results from a performance and subjective comparison among three sizes of touchpads, and, secondarily, between these touchpads and the default Glass controls; (3) characterization of personalization patterns and design considerations to support accessible wearable input for users with motor impairments.

RELATED WORK

We cover accessible mobile and wearable computing, as well as general wearable input and head-worn displays.

Accessible Mobile Computing

Mobile devices can provide a sense of independence for users with motor impairments [15,26], while presenting accessibility challenges [1,15]. For example, findings from Trewin *et al.* [33] and Anthony *et al.* [1] highlight the difficulty of multi-touch gestures. As well, users with motor impairments exhibit more errors with touchscreens than those without motor impairments [6], and users with gross motor impairments exhibit longer dwell times [14].

Approaches for addressing these challenges include making use of the edge of the screen to stabilize gestures [7,35] or using a swiping ("swabbing") interaction rather than tapping, which allows the user to stabilize their finger on the screen [34]. Based on analysis of touchscreen tapping, crossing, and directional gesturing by users with motor impairments, Guerreiro *et al.* [8] also found that targets located at the bottom of the screen and next to the preferred hand were the easiest to select.

These findings highlight both the positive impacts that mobile phones and touchscreen devices can have for users with motor impairments, but also the persistent need for more accessible means of computing in a mobile context.

Accessible Wearable Computing

Wearable device research for users with motor impairments has largely focused on wearable sensors for the diagnosis of medical conditions or in the context of motor rehabilitation; see [38] for a survey. Mazilu *et al.* [24], for example, used an inertial measurement unit to detect freezing of gait in

individuals with Parkinson's disease and provided audio feedback to help the wearer continue walking.

More related to our work, however, is accessible wearable *interaction*, that is, techniques to enable users to perform mobile computing tasks. McNaney *et al.*'s [25] study on the applicability of Google Glass for users with Parkinson's disease, and Carrington *et al.*'s [4] participatory design work on wheelchair-based input and output are two examples. In a follow-up to their original study, Carrington *et al.* [5] proposed a pressure-based touchpad input device mounted on the wheelchair's armrest that could be used to control a mobile device. As with the earlier design investigations [4], the focus here was not on controlling information on a head-mounted display; however, the approach could be used in that context. Although not focused on mobile interaction, other projects have investigated wearable input to control wheelchair movement (*e.g.*, using the tongue [12]) or to control desktop computers (*e.g.*, inertial sensors [29])—contexts which differ from a mobile computing scenario and from the head-mounted display scenario that is our focus.

Finally, the idea of using a head-mounted display to provide memory or other cognitive assistance for older adults [19] or users with cognitive impairments [10,36] has been investigated. In semi-structured interviews and shadowing with three older adults using Google Glass, for example, Kunze *et al.* [19] identified short-term memory augmentation, long-term capture and access, timers and reminders, and instructions (*e.g.*, for cooking) as potential application scenarios.

General Wearable Input and Head-mounted Displays

While not focused on accessibility, there is a long history of general wearable input research and research on head-mounted displays. Wearable input devices and techniques have ranged wrist-worn devices (*e.g.*, *GestureWrist* and *GesturePad* [30], *Facet* [21]), to rings (*e.g.*, [2]), to muscle-computer interfaces (*e.g.*, [31]), to on-body or skin-based interaction (*e.g.*, [9,11]). Many of these devices, particularly wrist-worn ones and rings, employ small interaction areas that may be difficult for users with motor impairments. Others could potentially be adapted to support a large input space for users who have difficulty with fine motor movements, such as *OmniTouch* [11], which employs a depth camera and projector to make any surface (including the body) interactive.

Most head-worn display work has occurred in the field of augmented reality (AR), where virtual imagery overlays physical objects in real time [37]. Applications have included such varied areas as military, navigation, industrial design, and medical [17]—even some smartphone apps offer AR functionality (*e.g.*, Yelp). To control the virtual information displayed, tangible user interfaces, gestures (*e.g.*, [20]), gaze tracking [18], speech input (*e.g.*, [27]), and other wearable devices such as Twiddler for text input [22] have all been investigated. In contrast to this previous work,

very little attention has been paid to accessibility in AR or more generally in the control of head-mounted display information—the head-mounted display work of McNaney *et al.* [25] and Kunze *et al.* [19] mentioned earlier are two rare examples. Our study begins to address this gap.

ACCESSIBILITY OF GOOGLE GLASS

To collect preliminary data on the potential impacts of a head-mounted display for people with motor impairments, we conducted a small study with one specific, yet popular device: Google Glass. While the findings from this study were limited to Google Glass, they motivated the subsequent and more general study on wearable touchpads.

Method

Six participants (4 female) with upper body motor impairments were recruited. Details are shown in Table 1.

Each session lasted one hour and included a background questionnaire (demographics and current mobile use), tasks with Google Glass, and a semi-structured interview on the experience of using the head-mounted display. Glass provides input through a touchpad on the right arm of the device that senses taps and swipes, and through voice commands. Output is through the head-mounted display that sits in front of the right eye and a bone-conduction headphone. For the Glass tasks, the researcher first demonstrated the touchpad and voice commands. The participant then completed a series of tasks over about 20 minutes, such as viewing activity on the timeline, looking up the weather, and taking pictures. To complete these tasks required at least 8 forward swipes, 3 backward swipes, 11 downward swipes, 12 taps, and 10 voice commands. Because of accidental taps and swipes, these numbers are a lower bound. For participants who could not reach the touchpad, the researcher performed that input.

Following the tasks, participants used 5-point scales to rate the physical comfort and ease of use of the touchpad and the visual display, and ease of use of the voice commands. The session concluded with open-ended questions about the potential impacts of head-mounted displays and brief feedback on design ideas for alternative forms of input beyond the built-in touchpad. Sessions were video recorded and analyzed to observe interaction successes and challenges, and to summarize open-ended responses.

Findings

Table 2 summarizes participant ratings on ease of use and physical comfort. Overall, ratings were neutral to positive.

ID	Age	Gender	Diagnosed Med. Condition	Mobile Device
P1	46	Male	Spinal cord injury (C5)	None currently
P2	25	Female	Cerebral palsy	Apple iPhone 5
P3	53	Male	Cerebral palsy	Basic phone
P4	25	Female	Cerebral palsy	HTC smartphone
P5	22	Female	Cerebral palsy	Apple iPhone 5S
P6	53	Female	Essential and orthostatic tremor	Basic phone

Table 1. Study 1 participants. All but P6 used a wheelchair.

ID	Visual Display		Touchpad Gestures		Voice Commands
	Comfort	Ease	Comfort	Ease	Ease
Median	2	2	3	2	1
M	2.2	2.2	3	2.7	1.7
SD	1.2	1.2	2.2	1.9	1.2

Table 2. Ease of use and physical comfort ratings for Glass interactions in Study 1 (1=very easy/comfortable to 5=very difficult/uncomfortable).

Input Mechanisms: Touchpad and Voice Commands

The accessibility of the touchpad depended on each participant's motor abilities. For P1, P3, and P5, the touchpad was not accessible at all and the researcher ultimately had to perform their taps and swipes. P1 and P5 could not physically reach the touchpad, although for P5 the touchpad may have been possible to use had it been on the left side of the device; she had limited movement in her right hand. P3, in comparison, could reach the touchpad but could not tap or swipe on it without physically displacing the device. After a few attempts, he asked the researcher to perform the gestures. The other participants, P2, P4, and P6, encountered fewer difficulties, although their error rates when attempting taps or swipes were still 11% (of 61 interactions), 37% (of 93) and 18% (of 65) respectively. For P4, by far the most common problem was that the touchpad did not respond to her input. This issue occurred 16 times, and was perhaps due to the angle at which she was able to approach the touchpad. She also had persistent trouble correctly locating the touchpad, despite intervention.

For voice commands, only P3 encountered difficulty. He had dysarthria (slurred speech) and for him the device only successfully recognized the word 'Google.' P1 and P4 expressed surprise at how well Glass recognized their voices. P2 suggested that Glass should be fully accessible by voice, and wanted voice commands like 'Go Back' or 'Home Screen' to replace swiping or tapping multiple times on the touchpad. These findings are in contrast to McNaney *et al.* [25], whose participants experienced issues with voice input perhaps because they used Glass in a variety of settings and for a wider range of tasks.

Visual Display

All participants were able to read text on the display when prompted. However, P3, P4, and P5 needed the display to be frequently adjusted because it moved when they tapped or swiped. P4 had problems keeping her head upright, which affected her ability to look at the display. During the session, she asked to be strapped to her wheelchair so that she could sit up and see the display better. Participants did not complain about the font size or size of the display.

Potential Impacts of a Head-mounted Display

Comparing Glass to a mobile phone, three participants mentioned the touchpad on Glass as a disadvantage. Advantages, however, included, not having to look down at the display (P2, P4), keeping the hands free (P2, P4, P6) and reducing the risk of dropping and damaging the device (P1). For example, P1 said:

ID	Age	Gender	Reported Medical Condition	Smartphone?	Uses wheelchair?	Dominant Hand	Box-and-Block Test	
							Right	Left
P1	46	Male	Spinal cord injury, C5	Yes	Yes	Left	0	16
P2	25	Female	Cerebral palsy	Yes	Yes	Right	8	2
P3	21	Female	Cerebral palsy	No Phone	Yes	Left	2	12
P4	23	Male	Spastic quadriplegia, neuromuscular scoliosis	Yes	Yes	Right	32	23
P5	25	Male	Cerebral palsy	Yes	Mobility scooter	Right	22	10
P6	23	Female	Cerebral palsy, Spastic quadriplegia	Yes	Yes	Left	0	4
P7	47	Male	Myotonic muscular dystrophy	Yes	No	Right	10	7
P8	31	Male	Spinal cord injury, C6 and C7	Yes	Yes	Right	29	11
P9	53	Female	Essential and orthostatic tremor	Basic Phone*	No	Right	53	48
P10	22	Male	Cerebral palsy	Yes	No	Left	46	46
P11	52	Male	Right side paralysis	Basic Phone*	Yes	Left	7	23
P12	61	Female	Hemorrhagic stroke	Yes	Yes	Right	53	0

Table 3: Study 2 participant demographics, smartphone use, wheelchair use, and Box-and-Block Test results for both hands (higher values represent higher manual dexterity). *P9 and P11 reported iPad use.

“That someone who has limited mobility could wear a technological device without fear of dropping or damaging it that seems a lot more useful than a notepad or a laptop in my aspect, in my living situation.” (P1)

P2 expressed the ease of not having to hold her phone:

“My hands are free. It didn’t require me to pick up anything as opposed to having to pick up this [phone] and you know look down on it and you know I was looking up so I didn’t have my head down.” (P2)

Feedback on Alternative Input Ideas

At the end of the session we briefly introduced theoretical alternatives to Glass’s touchpad: mid-air gestures, wearable physical buttons, and a portable touchpad. While the responses were generally positive, each participant had different yet specific places where they would like the touchpad to be located, like the armrest, joystick or tray. We explore this finding further in Study 2. Participants also spoke about using body and facial movements and customized voice commands as other alternatives.

Summary and Discussion

For our six participants, Google Glass presented exciting possibilities for mobile information access but also serious accessibility challenges. The always-available nature of Glass allowed easy access to information on the go, without the physical requirement to hold a mobile phone. At the same time, half of the participants could not use the touchpad input. These findings motivated our next study, where we evaluated personalizable wearable touchpads of different sizes to control Glass. Again, our goal is to design and assess alternate input systems for head-mounted displays like Google Glass that can provide mobile information access for users with motor impairments.

STUDY OF PERSONALIZED WEARABLE TOUCHPADS

To investigate the use of configurable, wearable touchpads for accessible control of a head-mounted display, we built a prototype system and conducted a controlled experiment with 12 participants with motor impairments. The study was designed both to assess user performance with different sizes of touchpad as well as to characterize how participants would want to customize touchpad locations.

Method

The study included three tasks: (1) a reciprocal tapping task to measure baseline performance with three sizes of touchpad; (2) another controlled tapping task, but with the touchpads placed at custom locations on the participant’s body or wheelchair; and (3) a more realistic task where participants used their preferred touchpad configuration to control a small app on the head-mounted display.

Participants

Twelve participants (5 female) with upper body motor impairments were recruited. See Table 3 for detail. To gain a baseline understanding of manual dexterity and variation across participants, we administered the standardized Box-and-Block Test [23]. This 5-minute test involves moving blocks one at a time across a partition and provides dexterity scores per hand. Typical adult scores range from about 80 for younger adults to about 60 for older adults [23]. Our participants’ scores, shown in Table 3, ranged from 0 (no use of the hand) to 53. Three participants (P1, P2, P9) had used Glass in the preliminary study, while the others had no prior experience. All participants were volunteers and were compensated for their time.

Apparatus

We built a custom, reconfigurable system that used four touchpads made of pressure-sensitive conductive sheeting to control a Google Glass device (Figures 1 and 2). The touchpads, each on a piece of flexible foam backing, were connected to an Arduino Uno board that sensed taps using the CapSense library. Touchpads of different sizes could be easily swapped out during the study. A Motorola MotoX phone running Android v4.4.2 acted as a mediator between the Arduino and Glass. The phone was paired with the Arduino via a BlueSMiRF HID Bluetooth modem, and communicated with it via the Amarino app [16]. This app received data about the taps from the Arduino and sent it to a custom Bluetooth chat application on the phone (built in Java), which in turn forwarded the input to Glass. An Android application was written for Glass to display visual task prompts and communicate with the phone. It also logged interactions with the wearable touchpads.



Figure 2: P12 performing Task 1 with large touchpads placed 32 cm apart on the table.

Procedure

Study sessions lasted two hours. The session began with a background questionnaire on demographics and technology experience, followed by the Box-and-Block Test. Participants were briefly introduced to Glass and tried out swipes and taps on the built-in touchpad. They then completed the three following tasks:

Task 1: Reciprocal Tapping. Participants tapped back and forth between two touchpads placed on a table in front of them (Figure 2). Three touchpad sizes were presented in counterbalanced order: 8 cm (large), 4 cm (medium), and 2 cm (small). The two touchpads (per size) were placed 32 cm apart, as measured from the centers of the touchpads. We chose these widths (W) and the distance (D) between them to cover a theoretical range of pointing difficulties. The Fitts' law indexes of difficulty (ID) were 2.3, 3.1 and 4.0 for the large, medium and small touchpads respectively, where $ID = \log_2(D/W+1)$ [13].

For each touchpad size, participants performed four practice taps (2 on each touchpad) using their dominant hand. The test trials were then presented—16 alternating taps—and participants were asked to tap as quickly and accurately as possible without stopping. The Glass display presented visual prompts to “tap forward” (right) or “tap backward” (left) for each trial. Success and error sounds played for correct and incorrect taps. The software only advanced to the next trial after the correct touchpad was tapped. After using each size, participants rated ease of use and physical comfort of performing the taps on 5-point scales. Overall feedback was solicited after all three sizes were complete.

Task 2: Location Customization and Tapping. Four touchpads labeled *forward*, *backward*, *select* and *cancel*, based on the four basic manual inputs of Glass were used. Sizes were presented in the same counterbalanced order as in the reciprocal tapping task. For each size, participants were asked to place the four touchpads anywhere on their body or wheelchair that was “accessible and comfortable” for them. The researcher affixed the touchpads to skin, clothing or the wheelchair using Velcro straps, Velcro tape, or adhesive tape (Figure 3).

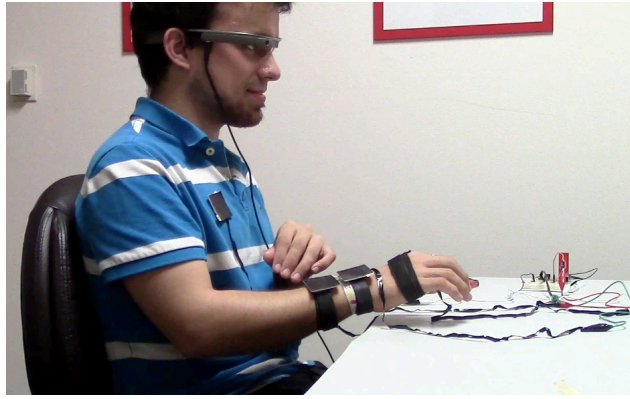


Figure 3: P10 performing Task 2 with the medium touchpads. He placed selected locations on the wrist, palm and chest.

Participants then tested out the touchpad locations and practiced tapping each one twice (a total of 8 taps), and were given the opportunity to adjust the locations if desired; 6 did so. Then, 32 test trials were presented (8 per touchpad). The order of prompts was randomized, with the constraint that no two consecutive taps could be on the same touchpad. As with the first task, participants were asked to tap quickly and accurately, and success and error sounds played. After each touchpad size, participants rated ease of use and physical comfort on a 5-point scale. They were also asked to provide rationale for their choice of locations. At the very end of the task, we asked about overall size and location preferences.

Task 3: Final Configuration and Realistic Use. Briefly, to provide a reminder of Glass’s functionality, we again had participants try the swipes and taps on the default touchpad (~1 minute). Then, to provide a more realistic experience of using wearable touchpads to control a head-mounted display, participants used a simple, custom Glass application. It included pictures, description and weather information on two cities, ordered hierarchically with 3 screens per city. Similar to Task 2, participants created a personalized input system by choosing different locations. In this task, however, they could select any size of touchpad and mix different sizes in case some were deemed to be more useful for particular locations. The four touchpads emulated the functionality of the Glass touchpad: *forward* and *backward* navigated the current level of the hierarchy, *select* provided more detail on an option (e.g., moving down a level in the hierarchy), and *cancel* closed the current page or returned to the previous level. Participants first tapped on each touchpad to make sure they could reach it and were given a chance to change the locations or sizes. Participants were asked to take a few minutes to explore the application, and had to try using each of the four inputs at least three times while doing so.

The session concluded with a final semi-structured interview on the experience of using the wearable touchpads and their potential impacts on accessibility of a head-mounted display. All interviews were audio and video recorded. P7 was not able to see the Glass display due to a

visual impairment, so for him all visual prompts were presented on a laptop screen instead.

Design and Counterbalancing

We used a within-subjects design with a single factor of *Touchpad Size*. It had three levels: *small* (2 cm), *medium* (4 cm), and *large* (8 cm). For a given participant, touchpad sizes appeared in the same order for both tasks. Order of presentation was fully counterbalanced, with an equal number of participants randomly assigned to each order.

Data and Analysis

One-way repeated measures ANOVAs with a single factor of *Touchpad Size* were used to analyze the timing data for each of the first two tasks. Post-hoc comparisons were protected against Type I error using Tukey HSD. Our primary performance measure is speed. The system did not advance until the participant had correctly completed the current trial, which means that *speed* includes an implicit error penalty. We do not present a separate error analysis because the system could not detect missed taps, such as hits just outside a touchpad's bounds.

While all participants completed the full study procedure, only 10 participants are included in these performance analyses for Tasks 1 and 2. For both tasks, the log files for P1 were not accurate because of a calibration issue with the touchpads. For Task 1 only, we excluded P6's performance data because we had to reduce the distance between the two touchpads to accommodate her limited range of motion. For Task 2 only, we excluded P4's performance data because he placed the small touchpads very close to each other, which caused interference for the capacitive sensing. In all, we analyze $2 \times 8 \times 3 \times 10 = 480$ trials for Task 1, and $4 \times 8 \times 3 \times 10 = 960$ trials for Task 2 (number of touchpads \times repetitions \times sizes \times participants).

For rating scale data, we used non-parametric Friedman tests. Finally, open-ended responses were analyzed based on themes of interest [3] (e.g., rationale, impacts of motor ability), while allowing for new, emergent themes.

RESULTS

We cover performance and subjective results for Tasks 1 and 2, as well as, based on Tasks 2 and 3, themes in personalization rationale and the experience of using wearable touchpads to control a head-mounted display.

Performance

Task 1: Reciprocal Tapping Task

This task provides a baseline performance assessment for the touchpad sizes in an ideal setup. As expected, *Touchpad Size* significantly impacted tapping speed. As shown in Figure 4, the average tapping time per trial was 2.7s ($SD = 1.3$) for the small touchpads, 1.8s ($SD = 1.0$) for medium, and 2.0s ($SD = 1.1$) for large. A one-way repeated measures ANOVA revealed a main effect of *Touchpad Size* on average trial completion time ($F_{2,18} = 8.57$, $p = .002$, $\eta^2 = 0.49$). Post-hoc comparisons indicated small touchpads were slower than both the medium ($p < 0.01$) and large ($p <$

0.05) sizes. No significant difference was found between medium and large sizes.

For subjective feedback, most participants ($N = 8$) found the large touchpad easiest to use, followed by medium and small ($N = 2$ each). The majority of participants ($N = 7$) also found the large touchpad to be the most physically comfortable, while 4 said medium, and 1 felt all sizes were similar. Participants provided ratings on ease of use and physical comfort, which are summarized in Table 4. While the mean ratings on both measures improve (i.e., become closer to 1) as the target size increases, Friedman tests were not statistically significant for either measure.

Task 2: Location Customization and Tapping Task

As with Task 1, *Touchpad Size* again impacted tapping speed. As shown in Figure 4, average trial times were 3.2s ($SD = 1.5$) for small, 2.5s ($SD = 1.3$) for medium, and 2.2s ($SD = 0.96$) for large touchpads. Across all touchpad sizes, these speeds are only 0.4s more than the baseline tapping speeds collected in Task 1, which shows that the personalized locations offer feasible input performance. A one-way repeated measures ANOVA revealed a significant impact of *Touchpad Size* on tapping speed ($F_{2,18} = 9.55$, $p = .001$, $\eta^2 = 0.51$). Post-hoc comparisons showed that the small touchpads were significantly slower than both the medium ($p < 0.05$) and large ($p < 0.01$) sizes.

Overall, large and medium touchpads appeared to be preferred to small touchpads for this task, with the following distribution of votes for most preferred size: 4 (large), 5 (medium), and 2 (small); one participant could not choose between small and medium. The ease of use and physical comfort ratings, shown in Table 4, support this trend. The mean ratings for the small touchpads were worse than for medium and large touchpads, although a Friedman test did not find a statistically significant impact of *Touchpad Size* on either measure. Encouragingly, the mean ratings for the larger two sizes were about 2 on a 5-point scale, meaning "easy" and "physically comfortable."

Personalization: Touchpad Placement and Rationale

We provide detail on placement and rationale findings from Task 2. Because rationale trends were similar in Task 3, where participants could personalize their input with

Task 1: Reciprocal Tapping	Small		Medium		Large	
	Comfort	Ease	Comfort	Ease	Comfort	Ease
Median	2	3	2	2	1	2
M	2.4	3.4	2.1	2.5	1.8	2.3
SD	0.9	0.9	0.9	1.2	0.9	1.3
Task 2: Location Customization	Small		Medium		Large	
	Comfort	Ease	Comfort	Ease	Comfort	Ease
Median	2	3	2	2	2	2
M	2.7	2.8	2.0	1.9	2.1	2.0
SD	1.2	1.1	1.0	0.8	1.1	1.1

Table 4. Ease of use and physical comfort ratings for Tasks 1 and 2 (1 = very comfortable/easy and 5 = very uncomfortable/difficult). ($N = 12$)

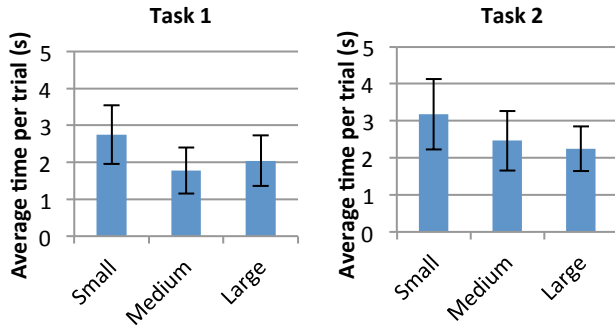


Figure 4: Average time per trial in Task 1 (reciprocal tapping) and Task 2 (location customization). The small touchpads were significantly slower than the other two sizes in both tasks. ($N = 10$; error bars: 95% confidence intervals).

multiple touchpad sizes at once, we highlight only the choice of sizes selected in that task.

Placement

In Task 2, participants chose a wide variety of locations for touchpad placement; see Table 5 for detail. Of the 8 wheelchair users, 2 placed all sizes of touchpad on their body only (thigh, wrist, palm, and chest), 3 chose their wheelchair only (tray and joystick), and 3 chose a combination of wheelchair and body locations. P5, on a mobility scooter, placed all touchpads on his body, “Because I’m not on my scooter all the time, it has to be on my body. It will be easier for me.” Among all the locations, the most popular choices were the thigh ($N = 7$) and wrist ($N = 5$). For wheelchair users, the tray was the most common location, followed by the joystick. While P9 and P12 chose the same locations for all three sizes, P1 and P5 had to adjust their configuration to accommodate the largest size (for P5 this meant using both thighs instead of one).

Rationale

Rationale for touchpad placement was an open-ended question and participants could provide more than one reason for each touchpad size. The reasons were similar across sizes, so we present an aggregate analysis.

As expected, participants’ motor abilities impacted their touchpad personalization. Overall, the most common reasons for selecting locations were ease of reach ($N = 8$) and proximity to the dominant hand/arm ($N = 6$). For example, P6 had a Box-and-Block score of 4 in her left (dominant) hand and we had adjusted the touchpad locations in the reciprocal tapping task so that she could reach. She accommodated this limited range of motion by placing all touchpads on her tray close to her left hand, saying: “I didn’t have to stretch too far.” As another example, P7 initially placed all large touchpads on his left arm. After the practice, however, he moved the topmost one to his knee because of the difficulty of lifting his arm high enough to reach it: “Easier to tap and [on the arm it had been] difficult for my hand to reach as far as I need to.”

ID	Small	Medium	Large
P1	Joystick, wrist, lanyard on neck	Joystick, wrist, lanyard on neck	Joystick, wrist, thigh, lanyard on neck
P2	Tray	Tray	Tray
P3	Tray, joystick	Tray	Tray, joystick
P4	Fingers	Fingers, wrist	Chest
P5	Thigh	Thigh	Thigh
P6	Tray	Tray	Tray
P7	Wrist	Thigh	Arm, thigh
P8	Thigh	Cushion of wheelchair	Thigh
P9	Thigh	Thigh	Thigh
P10	Chest, neck, palm	Chest, palm, wrist	Thigh, back of hands
P11	Joystick, armrest, wrist, thigh	Joystick, armrest, back of hand	Joystick, wrist, thigh
P12	Thigh, Wrist, Palm	Thigh, wrist, Palm	Thigh, wrist, palm

Table 5. Choice of touchpad locations per participant per size. All but P5, P7, P9, and P10 use a wheelchair.

Another anecdote on the impact of personalization comes from P8, who described a problem in how he typically uses his touchscreen phone. He cannot point perpendicularly to the screen because the low strength in his hand causes instability when the fingers bend. Instead, he taps the screen with his knuckles. With the personalized layout he placed the touchpad sideways on the wheelchair cushion, which allowed for tapping with the side of the hand; Figure 5. He thought of this option in time for the last touchpad size (medium in his case), saying, “It was just easy.”

Three participants (P8, P9 and P12) talked about placing the touchpads close to where their hands rest in their natural state. For P9, the desire to rest her hands was due at least partly to her tremor. She said before initial touchpad placement: “I mean most naturally my hands would rest here [points to thigh] so like I guess on my thighs.” Other reasons for placement included arranging touchpads based on their meaning (e.g. *forward* in front of *backward*) to remember the order ($N = 4$), wanting the touchpad to be easily visible ($N = 3$), reducing interference with the wheelchair ($N = 2$), and using familiar locations ($N = 10$).

Finally, three participants commented on the emergent benefit that their touchpad placement allowed for eyes-free use so they could maintain visual attention on the head-mounted display—an important practical consideration for control of such a display.



Figure 5. Large and medium personalized touchpad placement for P8, showing a perpendicular approach that requires bending at the knuckles (left) compared to an “easy” approach from the side with vertically placed touchpads (right).

Interference with Typical Movements

An important potential downside of wearable input is the possibility of interfering with typical body movements or other worn items. The majority of participants ($N = 8$) felt that the large touchpads would interfere with body movements, and few ($N = 4$) also felt they would interfere with items worn on their body. P1, for example, said of the large size, "...they would alter the way I would normally do things." Only at most 3 participants felt the small or medium touchpads would interfere with body movements, worn items, or wheelchair movements. Two participants (P8, P9) had mentioned taking interference into account during touchpad placement. Another issue considered by P12 is that an ideal placement while seated may be different while walking.

Overall Location and Size Comparisons

Preferences regarding the touchpad sizes after Task 2 varied. The surface area of the large touchpads was an advantage for some participants as it did not require precise tapping (P5, P11), but a disadvantage to others, who felt that it led to accidental taps (P6 rested her hand close to the touchpads), was too cumbersome (P9), or took up too much space (P6, P7, P8). The small touchpads, however, provided more options for placement (P6, P9) but required more precise movement (P7, P12). The medium size was a nice compromise for some (P5, P7, P8, P12). When asked to compare locations they had tried across the three sizes, many responses were similar to the earlier rationale responses (e.g., thigh is easy to reach). P1, however, commented that the lanyard placement he had used was difficult because it made for a moving target.

In Task 3, participants mixed different sizes to create a personalized input system with four controls. The variation in choices again supports the need for personalization. Eight out of 12 participants combined different sizes: 4 used medium and large, 3 used small and medium and 1 used all three sizes. Other participants used all small (P1, P9), all medium (P8), or all large (P4) touchpads. Dominant reasons provided for these choices were similar in pattern to those at the end of Task 2, such as ease of reach.

Comparison to Glass's Built-in Touchpad

Participants used Glass's built-in touchpad twice during the study: once as an introduction and briefly as a reminder before Task 3. The wearable touchpads were considered by almost all participants to offer accessible control of a head-mounted display, and compared favorably to Glass's built-in touchpad. While 4 participants (P1, P3, P6, P7) could not reach the touchpad on Glass, all 12 were able to use the wearable touchpads to complete the study tasks. Six of the 8 participants who *could* reach the Glass touchpad still felt that the wearable ones would positively impact their ability to use a head-mounted display, for example, "*More accessible*" (P10), and:

"For me, with my arm and hand issues, its much more difficult to keep going here [points to Glass] than it is to rest my hands on my lap and just tap what I need to." (P9)

When asked how the wearable touchpads would impact their ability to independently use a head-mounted display compared to Glass's touchpad, 9 felt that the wearable option would provide more independent use, and 2 thought the options were similar. That said, one participant (P12) mentioned an important drawback of the wearable approach—that it requires effort to do the customization rather than having an all-in-one device.

As it did with placement rationale, the desire for eyes-free input arose again. Participants were split on how the wearable option would impact their ability to pay attention to their surroundings. On the positive side ($N = 6$) were participants like P9, who felt the wearable touchpads were easy to tap without looking, "*Because I got to choose where they were [...] plus it was all kind of the same movement.*" On the negative side ($N = 2$), P12 appreciated that Glass's default input was designed to not require visual attention.

Social Considerations

Issues such as aesthetic design and social awkwardness are common with wearable devices [28], and, unsurprisingly, a few participants mentioned such concerns. P1 and P9 felt the large touchpads would be awkward to use in a public place. P8, who had placed the touchpads on the cushion of his wheelchair for his personalized setup said:

"You're a bit more incognito [than with Glass's touchpad...] I could sit there for a while clicking on [the wearable touchpads] and I bet this [Glass's touchpad] would be weird and stupid and annoying sitting over here tapping on my face for longer than 30 seconds or 8 taps."

One participant mentioned stigma around assistive technology [32], a concern that could be magnified in the context of wearable devices. P1 said of the large touchpads:

"...I don't want to look like R2-D2. I want people to see [name] and not his [wheel] chair so I would not use these big ones [...] they stand out too much."

Some participants offered new ideas for controlling the head-mounted display, and again social considerations arose. P8 compared head movements to voice input, saying: "*Speaking is not something I want to do in public, only nodding to cancel is something I would want to do.*"

DISCUSSION

The two studies presented here extend a small body of recent work [4,25] by both motivating the need for further research on accessible input for head-mounted displays and by providing promising directions for how to provide that input. In Study 1, participants reacted positively to the idea of using a head-mounted display, as embodied by Google Glass. Compared to smartphones, potential advantages included not having to hold the device while interacting with it, not having to look down to see the screen, and not having to worry about dropping the device. While preliminary, these findings suggest that such a device may offer important opportunities to increase mobile computing accessibility for users with upper body motor impairments.

Design Reflections

The findings from Study 2 point to the promise of a wearable switch-based control that can be personalized to a user's motor abilities. All 12 participants were able to use the wearable touchpads to control the display, including those four who could not use Glass's built-in touchpad. The relatively small difference between performance in the baseline condition (reciprocal tapping on the table) and the wearable condition supports the feasibility of our approach in terms of providing efficient input. Finally, in contrast to work with wheelchair users only (e.g., [4]), our participants also included non-wheelchair users and one person with a mobility scooter. This diversity provides a degree of generalizability to the population of users with upper body motor impairments, although more work is needed.

The utility of personalizing wearable input to support individual motor abilities was demonstrated in Study 2, and provides evidence to strengthen suggestions made in previous work [4]. Participants selected varied locations (wrist, thigh, arm, tray, armrest) for the wearable touchpads and even mixed sizes when given the opportunity. The most common reason for selecting a location was "ease of reach," with detailed description often revealing the participant's consideration of their motor abilities. A downside of personalization is the effort required (e.g., mentioned by P12) and the potential, particularly for wearable input, that the input device will need to be adjusted each day. An important area of future work is thus to investigate easy-to-adjust wearable mounting mechanisms or permanent placement on the chair itself for wheelchair users. Carrington *et al.*'s [4] chairables work provides guidance in this latter direction.

Wearable touchpads do present some practical issues. The possibility of interfering with everyday activities such as body or wheelchair movements was of particular concern with the large touchpads. Smaller touchpads may mitigate this issue. Capacitive touchpads, as used in Study 2, are also not likely to be the best approach. Although they require little strength to activate, they are also more susceptible to being accidentally triggered than a mechanical button would be. However, the findings from our study should apply to other switch-based input if the goal is to support personalization.

Our focus was to build a solution that could: be socially acceptable, support use in a mobile context, be easy to learn, and be accessible to users with varying levels of physical strength. Our wearable touchpad approach supported these goals, yet is only one potential solution. Alternatives to manual input will also be important to explore. For example, ideas of eye-gaze and head-controlled input were raised by our participants. Expanded speech input offers another possibility for accessible control of a head-mounted display, but it was not usable for one Study 1 participant due to dysarthria, and was mentioned as

inappropriate for social reasons in Study 2. The need for accessible manual input remains important.

Limitations

While the wearable touchpad approach should be applicable to head-mounted displays in general, the accessibility findings in Study 1 are specifically limited to Google Glass; different issues may arise with other devices. As well, our evaluations were limited to a lab setting and users with mild to moderate impairments in their hands and arms. To truly understand the impacts of this approach, future work will need to assess performance and user response in a variety of mobile contexts and include users with more severe motor impairments. One Study 2 participant, for example, mentioned the possibility of having multiple sets of touchpads at different locations, like his desk and scooter, for everyday use. Additionally, participants were seated during study tasks and the touchpads were wired, which may have influenced placement (e.g., popularity of the thigh). We note, however, that the wires only rarely interfered with the participant's ability to tap. We plan to create a more robust wireless approach in the future. Finally, we examined switch-based input, which results in the need for multiple controls (in our case four touchpads to control Glass). For users with sufficiently fine motor control, there may be a preference for using a single touchpad that would support swipe gestures instead of having to use four touchpads that only support tapping.

CONCLUSION

We presented two studies investigating accessible control of head-mounted displays for users with upper body motor impairments. The first study, while small, offered potential advantages of a head-mounted display over more widely used mobile computing devices, such as not requiring that it be held during use. At the same time, we identified accessibility challenges with Google Glass. Glass is of course only an early example of mainstream head-mounted displays, and we expect improvements in the coming years. The personalized wearable approach that we proposed and evaluated in Study 2 offers one promising direction.

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