Typhlex: Exploring Deformable Input for Blind Users Controlling a Mobile Screen Reader

Deformable inputs offer blind users the ability to physically manipulate a device for system interaction. The authors describe the iterative design process of a deformable device prototype—Typhlex, with strategically placed grooves to elicit bend gestures—and lessons learned from two user studies.

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A 2014 online survey of mobile phone users revealed that 91 percent of the survey's visually impaired respondents owned an iPhone.[1] Yet such touch-centric smartphones present strong challenges for blind users: with no tactile reference to anything other than edges or corners, blind users cannot interact with the visual interface or process its feedback. This creates accessibility challenges and reduces access to the wealth of information available through today's mobile technology. Currently, to interact with a touch smartphone, a large proportion of blind users depend on audio cues from screen readers to understand the system status and perform generalized swipe and tap gestures to navigate and select content. However, because the touch gestures must be highly accurate and often require multifinger use, learning and executing the gestures can be difficult.[2]

Deformable devices offer an enhanced tactile interaction model, because users interact with the interface by performing physical manipulations, such as bending, twisting, or squeezing.[3,4] For a demographic that relies heavily on touch, this tactile form of input could potentially let blind users further interact with the world around them. (For more information, see the "Related Work in Deformation Gestures and Accessibility Technologies" sidebar.) Learning and performing these intuitive deformable gestures on easily locatable and distinguishable parts of a smartphone, such as corners and edges,[5] could help blind users interact with screen readers.

Our main goal is to explore the novel concept of deformable user interfaces for blind users to better understand if a more tactile experience could enhance the usability and accessibility of mobile technology for such users. Specifically, we wish to contrast bend gestures with the commonly used touch gestures in controlling a mobile screen reader—a typical task performed by blind users to browse websites on their smartphones. We aimed to define deformable interaction paradigms that are comparable to touch (in terms of performance, comfort, and tactility) for blind users and that have high understandability and learnability traits for novice users.

Here, we report on our initial effort in developing deformable user interfaces for the visually impaired—specifically, on the iterative design process of our deformable prototype, Typhlex, and the gesture set it supports as an

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Related Work in Deformation Gestures and Accessibility Technologies

We describe related work on deformation gestures—in particular, their distinction from touch and their activation methods. We then present existing accessibility technologies for blind users that inspired our Typhlex deformable prototype.

Deformation Gestures

A growing body of researchers is finding deformation gestures—such as bending, squeezing, and twisting—to be both intuitive and complementary to touch.[1–3] In contrast to touch gestures, typically parameterized by the location of activation, bend gestures offer multiple degrees of freedom, including the location of activation (the top corner of the device, for example), direction of the bend (such as up/down or inward/outward), and sometimes even the magnitude of the bend,[4] allowing for more elaborate user input. The counter force generated from the deformation also provides tactile feedback, which is absent from touch-enabled devices that are mostly rigid.

Deformable gestures also encompass activation by both hands[1–4] or by a single hand.[5] In the prior case, either each hand provides an opposing force to create a deformation (for example, both hands exert a downward force to create a bend in the middle), or one hand creates a structural hold[6] for the other hand to complete the gesture. In the latter case, the same hand generates all the necessary forces to create a deformation (for example, one hand squeezes on both sides to create a bend in the middle). Our previous study on one-handed deformable interaction[5] has shown promise in improving comfort and performance on a mobile device.

While researchers have explored many contexts of use, we found no prior work on deformation in the context of accessibility or for the visually impaired, besides our previous work focusing on the design of bend gestures for blind users.[7] We extend our existing work by detailing the design process used to improve our deformable device, and we explore how it can support mobile activities of blind users.

Accessibility Technologies for Blind Users

Visually impaired users struggle with the usability of both software and hardware. It is not uncommon for a blind user to carry three or four devices to perform specific tasks: mobile phones, laptops, Braille PDAs, and audiobook players. Furthermore, they often face usability issues with touch devices—for example, they experience difficulty in learning objects' on-screen locations and sometimes accidentally activate features due to unintended touches.[8]

The release of Apple's VoiceOver (www.apple.com/ca/accessibility/mac/vision) and Google's TalkBack (https://play.google.com/store/apps/details?id=com.google.android.marvin.talkback) in 2009 provided visually impaired users access to the newly emerging smartphone market in a single device. Yet, there are usage and usability concerns with these touch-based screen readers, including a lack of logical navigation order and orientation, inconsistent focus, conflicting app and system controls, and difficult text input.[9] Shaun Kane and his colleagues found that blind participants' gestures included more strokes, exhibited a preference for the screen's edge or corner, and used more abstract shapes.[10] Based on these findings, the authors recommended favoring edges and corners and reducing the need for location accuracy when designing touch interactions. We applied these recommendations to the activation areas of Typhlex.

Researchers also explored alternative input methods, predominantly through auditory or tactile approaches. For example, BlindSight uses audio feedback and the keypad on a mobile phone to replace operations that need a visual interface,[11] earPod uses a modified circular touchpad with audio feedback to allow eyes-free menu-item selection,[12] and BrailleType uses audio feedback for a blind user to input Braille characters with touch.[13] To this end, we contribute by exploring the use of bend gestures and assess their validity as input methods for blind users.

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alternative input to a mobile screen reader (see https://youtu.be/bn16dH-BBfx0). The design process involved usability testing sessions with sighted users (with the prototype hidden from view to simulate a visually impaired situation) and blind users, whose feedback helped guide prototype development.

Design Process of Typhlex

We employed an iterative design approach to develop Typhlex, which gets its name from a combination of the Greek word "τυφλός," meaning blindness, and the word "flexible." We designed and fabricated Typhlex as a one- or two-handed deformable device, and we established a gesture language used by blind users for mobile screen reading (see Figure 1). We then conducted two user studies and, after each one, we improved the prototype based on our observations and user feedback. This article summarizes and extends our previous work,[6] which focused on the deformable gestures design and an exploratory study with simulated blind participants. Here, we detail the design process of the prototype and report on a small study that included actual blind participants.

Designing the Initial Prototype

We began the design of Typhlex with a deformable device developed for smartphone usage.[7] Although we conceptualized the prototype as an external input device connected to a smartphone, in the future, it could incorporate components of a smartphone and become a single unit for greater portability.

Prototype fabrication. We created Typhlex as a portrait-oriented device so it could be easily held and used with one hand if preferred. We designed it to perform at least eight basic bend gestures, allowing basic site navigation and browsing preferences (including read/select an item, select previous/next item, select previous/next based on a secondary action, and change the rotor setting). We fabricated the prototype similar in size to an iPhone 6 (120 × 72 × 10 mm) using silicone resin (Alumilite 70A), and we embedded four bidirectional FlexPoint sensors to measure the magnitude of each bend individually.

To better define the bending locations and improve the ease of bends, we placed protrusions in the mold during the casting process to create grooves on the back of the device. This process created thinner depths at specific locations, creating flexible joints and allowing more defined and easier bends. We borrowed the industrial design concept of "strain relief" used to strengthen the connection between the cable and connector in modern power and computer cables, and we inversed its effect to create a strain point where the device should bend.

We tested several versions with a small group of deformable gesture experts from our research lab, iterating variations in groove location, width, and depth to evaluate performance and usability (see Figure 2a). Feedback indicated that a more dispersed groove pattern (version 11) created a balance of defined joint bend, device rigidity, comfort, and less interference from other gestures given our prototype's characteristics.

Gesture classification. To ensure consistency with real-world applications, we adopted basic touch gestures established in Apple's VoiceOver software. These included swiping left and right for navigation, swiping up and down to navigate additional actions, rotating with two fingers clockwise- and counter-clockwise to change the rotor setting, and double tapping to select the focused item (see Figure 3a). We used a set of bend interactions on one-handed gestures for a device in portrait orientation previously evaluated elsewhere,[7] and we mapped the corner, top, and center bends (see Figure 3b) to these gestures, as detailed in our earlier work.[6]

Preliminary User Study with Sighted Participants

We first evaluated Typhlex (version 11) using sighted participants with the prototype hidden from view to simulate visual impairment. This methodology was comparable to previous work[8] and

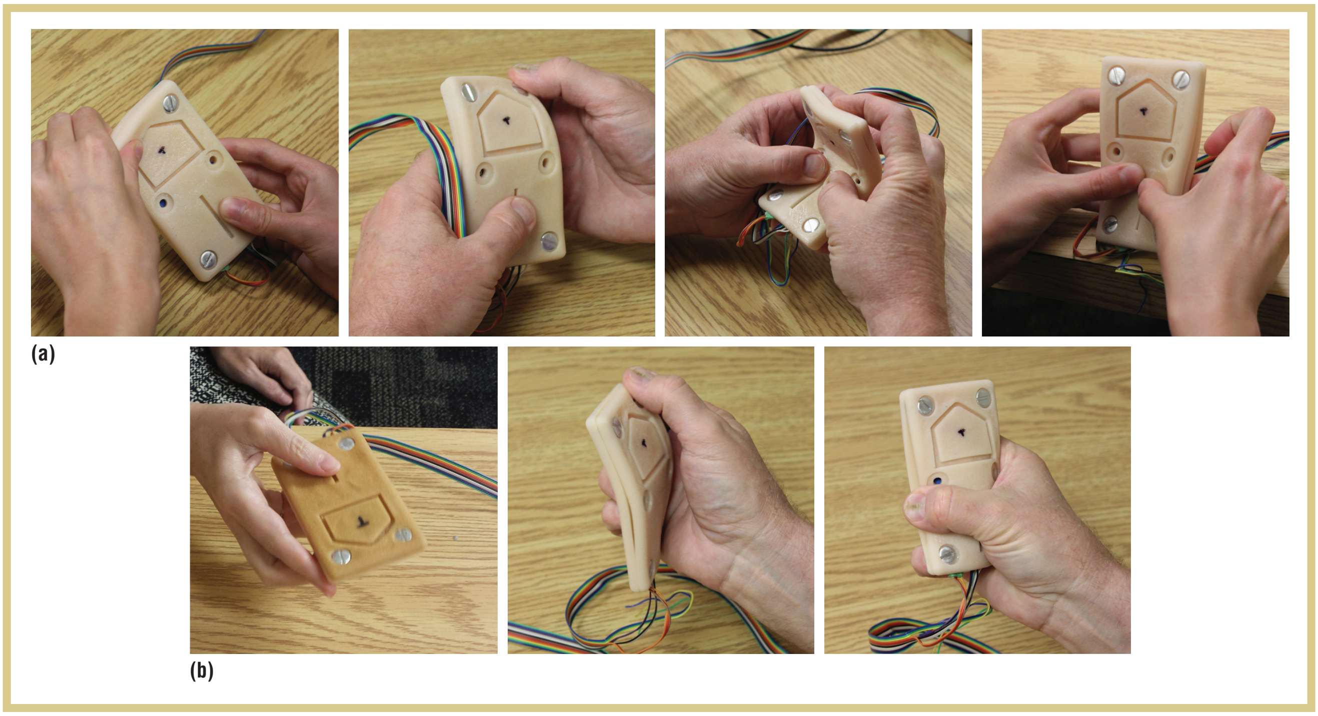

Figure 1. Blind participants control VoiceOver by manipulating our updated deformable prototype Typhlex with (a) two hands and (b) one hand.

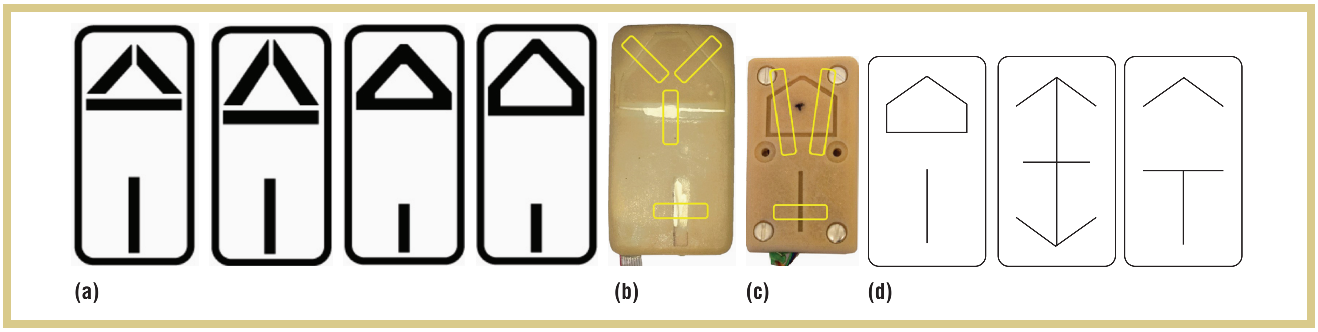

Figure 2. We tested several versions with a small group of deformable gesture experts from our research lab: (a) the initially tested groove placements with (b) the original prototype and (c) the smaller, updated prototype (with the sensor placements shown in yellow), and (d) three additional groove placements tested.

enabled simplified and quicker participant recruitment. We were aware of the discrepancy with sighted participants (blind users have a heightened sense of touch, for example), yet we believed it was sufficient for a preliminary study to evaluate Typhlex as a deformable input for a screen reader and gain insights to improve the prototype. We predicted that due to the user's sole reliance on non-visual feedback (tactile cues and audio), bend gestures would be a preferred method of interaction over touch.

We recruited 17 sighted participants (10 male, 7 female) between the ages of 21 and 44 (the mean age was 31). Each participant performed three web-browsing interaction tasks: navigating a list, performing additional actions (such as archiving or deleting content), and changing the function of the rotor setting. Each participant also completed the same three tasks using a touch prototype of the same dimensions, embedded with a capacitive touchpad. We counterbalanced the order of inputs (bend, touch) and randomized the order of tasks. We tested our interfaces on an audio-based interface created with HTML and Speak.js,

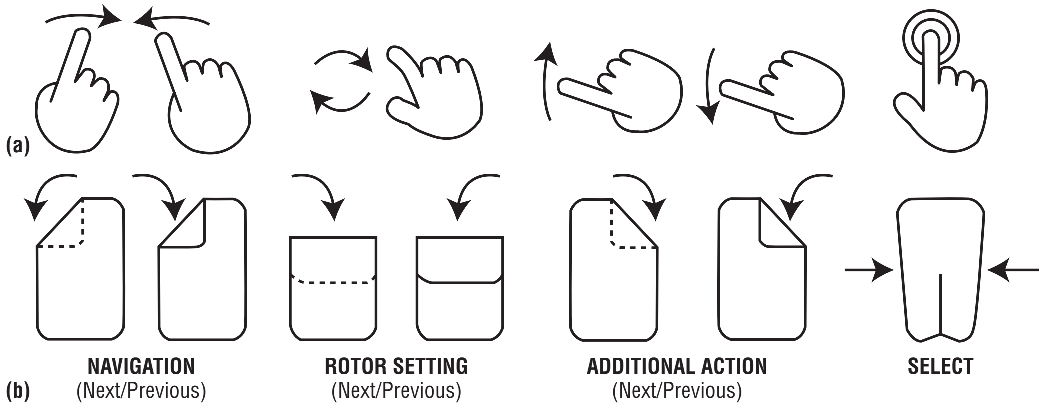

Figure 3. We adopted basic touch gestures established in Apple's VoiceOver software. These included (a) swiping left and right for navigation, rotating with two fingers clockwise- and counter-clockwise to change the rotor setting, swiping up and down to navigate additional actions, and double tapping to select the focused item. We then (b) developed associated bend gestures for each touch gesture.

due to limitations in native OS voice reader integration.

We measured the completion time and asked participants to rate their level of comfort for each task and gesture. For the action task, participants using bend gestures took on average 43.1 seconds (standard error = 7.0 s) compared to 34.7 s (SE = 2.8 s) for touch gestures. For the navigation task, participants using bend gestures took 20.4 s (SE = 2.6 s) compared to 19.0 s (SE = 23.3 s) for touch gestures. Finally, for the rotation task, participants took on average 22.2 s (SE = 4.0 s) with bend gestures versus 16.2 s (SE = 1.7 s) with touch gestures. We found no significant difference between completion times for bend and touch gestures. Participants had a slight preference for bend gestures (10 of the 17 participants).

We refer readers to our previous work[6] for a more detailed report of the study. We highlight here our observations and user feedback that inspired the next iteration of Typhlex:

- Participants often regripped the prototype to switch between bend gestures—that is, they repositioned their hands in preparation for a bend at another location on the prototype—resulting in a longer-than-expected time to complete the bend tasks.
- Participants who preferred using bend gestures to complete the tasks commended the ease of bend gestures and better mapping of the action to the task (for example, up and down mapped to navigating up and down in the list).
- Participants identified the bends as providing a more tactile form of interaction. The grooves on the back of the prototype, originally created to facilitate bends, unintentionally helped participants identify different corner locations, differentiate between tasks, and avoid confusion.

We also evaluated our prototype informally with two visually impaired participants, one fully blind and one with low vision, to collect insights from our target demographic. Their impressions aligned with our findings from the sighted participants that the spatial separation of the interactions was positive for bends, further supporting the prototype's readiness for use. They also suggested making the prototype smaller, using different material textures for identifying bend locations, and having more pronounced grooves.

This study demonstrated the potential of bend gestures to control a mobile screen reader in a nonvisual environment. Its results also informed us to update our prototype in terms of its size (for the regripping issues) and composing materials and surface texture, and to explore other groove positions to provide ease of corner identification.

Updating the Bendable Prototype

We redesigned Typhlex to more advantageously use bend gestures in a screenless input device: we reduced its size (see Figure 2b and 2c) close to that of a third-generation iPod Touch, comfortable to hold in the palm of the hand, to address the regripping issues while allowing portrait and two-hand usage if desired. The new prototype was 90 percent of the original width and 85 percent of the original height ($109 \times 61 \times 12.7$ mm). We tested three additional layouts with the same small group of deformable gesture experts and solicited feedback on changes in groove and sensor placements to facilitate bend joints (see Figure 2d).

After testing for ease of bends and identifying bend locations, we determined that our original bend sensor layout in version 11 was optimal and resulted in more consistent gestures. However, we made the grooves thinner and duplicated them on the top and bottom of the device. This made the prototype easier to bend upward while providing a tactile identifying marker on the top of the device for where to bend, as previously suggested by our informal blind participant. We refined the grooves to have more precise and consistent placement by 3D printing the mold as two identical cavities, and we used a more flexible silicone resin (Alumilite 60A) for easier deformations. The 3D-printed mold created a slightly rough surface texture. We also reduced the number of bend sensors to three to save space (see Figure 2c) while detecting all of the original gestures. Therefore, this updated prototype was comprised of two identical top and bottom silicone pieces, held together using bolts flushed to its surface, with the bend sensors and circuit sandwiched in-between. This construction allowed better access to the sensors and wires.

User Study with Blind Participants

We conducted our second study to explore deformable gestures with blind users recruited from local blind support groups. We compared our updated prototype with a smartphone by asking participants to browse a mobile website performing a series of common tasks while controlling a screen reader.

To better align the evaluation conditions with the current, real-world experiences of blind users, we replaced the Speak.js library with the VoiceOver software and used a live website instead of a simplified one designed for experimental purposes. We also selected an iPhone 6, a common smartphone among our participants, as our touch condition, and we changed the secondary bend interaction (top left corner) from performing additional actions to navigating the links on a page.

Methodology

During the study, we verbally described the system to participants and allowed them to practice each interaction with the audio feedback until they felt comfortable with the setup and prototype. We tested the same three browsing tasks as in the preliminary user study: navigating through webpage document object model (DOM) elements (navigation), navigating through webpage links (action), and changing the function of VoiceOver's rotor setting (rotor). We designed a 2×3 repeated measures within-participant study, where the first factor, Interaction, consisted of "bend" or "touch," and the second factor, Task, consisted of "navigation," "action," or "rotor." Each participant performed three trials for every Task (9 trials total) and with each Interaction (2 Interactions $\times$ 3 Tasks $\times$ 3 trials = 18 measurements per participant). We counter-balanced by Interaction (with half of the participants carrying out the tasks using bend first, and the other half using touch first), and we randomized the task order.

We captured general observations and user preference for each interaction technique through a questionnaire and short post-experiment interview. The study lasted approximately 60 minutes.

Participants used the seven bend and touch gestures from the preliminary study (Figure 3) to navigate through a YouTube mobile website using both the iPhone 6 and Typhlex. During the touch portion of the study, we loaded the mobile website through Chrome on the iPhone and used the native iOS VoiceOver touch gestures and audio feedback. During the bend portion, the prototype triggered keyboard presses, which allowed users to navigate the same mobile website loaded through Chrome on a Mac laptop. Participants received similar VoiceOver audio feedback from the computer by adjusting the settings to achieve a consistent speech rate, pitch, and voice type with that of the iPhone.

Analysis

Because our goal was to evaluate the next iteration of Typhlex and validate our preliminary findings with actual blind users, we determined that completion time was an inappropriate comparison metric. Blind participants were typically experts at touch gestures with VoiceOver, while being complete novices with bend gestures, so we could not draw conclusions regarding the efficiency of bend gestures. Instead, we focused on the initial use, collecting data in the form of observations and user feedback, which revealed participants' experiences with the learnability, comfort, and physicality of bend gestures.

Due to the limited availability of blind participants, we evaluated our prototype with three legally or totally blind participants (two male, one female), aged early 20s, mid-30s, and early 60s—different from our first study's informal participants and all of whom had no experience with bend gestures but were familiar with smartphones and VoiceOver. We compensated each participant with $20 Canadian dollars.

Understandability and learnability of bend gestures. All participants quickly understood the concept of bend interactions with little verbal explanation as reflective of past work[3] and our first study's findings. The top corner bends proved the easiest to introduce, with the grooves providing a teaching tool and tactile reference during the training. Some participants required more explanation to understand the top bend, because they were unsure what part of the device defined the "top." Squeeze-to-select was the most difficult gesture to introduce and was often confused at first with pressing the device (similar to a button). One participant suggested describing the action as "folding the sides in" instead. All participants easily remembered the seven bend gesture mappings after the training and used them during the tasks with little prompting. One participant found the bend gestures to be similar to actions learned as a child, so the participant could easily conceptualize what action to perform. This contrasts with some touch gestures, which were more difficult to learn.

To understand the initial handling configuration of Typhlex, we limited our instructions about device orientation. This enabled the proper mapping of the bend sensors to directional interactions but enabled participants to freely hold the device in any manner they wished. All our participants naturally defaulted to a two-handed hold (Figure 1a), which was comparable to our first study, where most participants also held the device with two hands. Participants moved their left or right hand to the corner to perform a corner bend, or they pushed their thumbs in to perform a selection. Up bends seemed easier to perform than down bends and required less hand repositioning. Figure 1b illustrates some gestures performed with one hand.

Our post-experiment interviews focusing on perceived learnability of the gestures and comfort revealed that bend gestures were potentially easier to learn. Due to the limited sample size for the study, we could not gather conclusive data. We instead use this data to illustrate the potential advantages of bend gestures. For example, one participant compared our experiment with her experience in learning the touch rotor interaction, which was "very hard" to learn; it took her two months to master the interaction due to the complexity of the gesture. She indicated that multiple people tried to teach her how to perform the gesture, yet no one could relate to the required finger placement. Further research could explore the comparative learnability of bend gestures versus touch with novice users who have no experience with either interaction models.

Usability and accessibility of Typhlex. All participants noted the innovative nature of Typhlex as a deformable input device. One said that "the simple interface is fantastic" and that it was "overall a pretty good prototype." Another said that it was an "interesting device" and indicated that this was "just another way of doing things," but this person did not find any benefit—at least "not yet, probably because of the learning required."

Regarding usability, all participants successfully completed all tasks using Typhlex with minimal guidance and training. One participant mentioned the systematic nature of the bend interactions over touch as positive, but also added that the ability to freely move the finger around the screen and "explore the UI" was missing, which was not incorporated in our prototype. Another participant mentioned that squeezing provided "more assurance that I did something than the double tap," because sometimes double taps would also trigger a swipe touch gesture. They identified that the bend gestures were clearly distinguishable from each other and would not cause this double interaction. Participants appreciated the ability to perform the squeeze action by either folding up or down, because all three performed the action in both directions.

We observed participants using their thumb to sense the grooves on the device's top to determine where they should bend, more than those underneath. Most participants explicitly mentioned liking the material and texture of the updated prototype. Participants suggested that stiffening non-bendable areas would help creating more defined bend gestures during testing.

On the other hand, one participant mentioned the lack of refined indication on how much to bend. Large curvatures (over-bending to perform an action) were common across all participants, and identifiable feedback should be included to identify how much to bend.

Initial Design Recommendations

Based on our experience with Typhlex, we present initial recommendations for designing deformable input devices for blind users—in terms of the form factor and associated interaction paradigm—to provide insights in designing devices of a similar nature.

Use groove positioning to guide and facilitate bends. Grooves can be used as both strain relief (to make bending easier) and as guides for blind users to locate bendable parts through touch. These grooves should be strategically positioned to provide sufficient spatial separation to allow distinguishable bends, and they should appear on both sides of the device to optimize locating them through touch.

Support one- and two-handed use. We designed Typhlex's size to be comfortably held and used with one hand. However, it is important to consider two-handed uses when designing the shape and size of the device, as observed in our user studies. Although it requires an additional hand, this hold provides better structural support for bend gestures and thus could allow more sophisticated interactions.

Provide indication of how much to bend. Because a bend gesture can be determined by its location, direction, and magnitude, the designer should incorporate a feedback mechanism to indicate how much to bend—a feature requested by our blind participants.

Combine various stiffness levels to widen bend gestures. We fabricated Typhlex using one type of flexible material and relied on the grooves to indicate bend locations. By using materials with different levels of flexibility, it might be possible to better define bend gestures and allow greater variation in composite bends. This could also increase production feasibility by letting designers and manufacturers embed nonbendable components in the stiffened areas of the device.

As illustrated by our prototype, bend gestures were easily understood, performed, and enjoyed by our participants, and the gestures provided a more familiar mapping to screen-reading actions than touch-based interaction. However, there was room for improvement in the technology, manufacturing, and industrial design for deformable inputs in increasing blind users' performances to complement the commonly used touch input paradigm. This work opens the door to further research in providing new technology and interaction patterns through tactile feedback to improve the overall accessibility and usability of smartphone technology for blind users.

We aim to explore the use of bend gestures with a more sensitive prototype in a longitudinal study, evaluate the learnability and usability of bend gestures for blind users who have no experience with touchscreen-operated VoiceOver, and evaluate usability for tasks other than website browsing. Overall, we see deformable input as a promising complement to the existing mobile interaction language, which relies heavily on touch. Deformable input could greatly improve the accessibility of mobile interaction, reaching a wider user demographic—especially blind users.

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