# Typing Slowly but Screen-Free: Exploring Navigation over Entirely Auditory Keyboards

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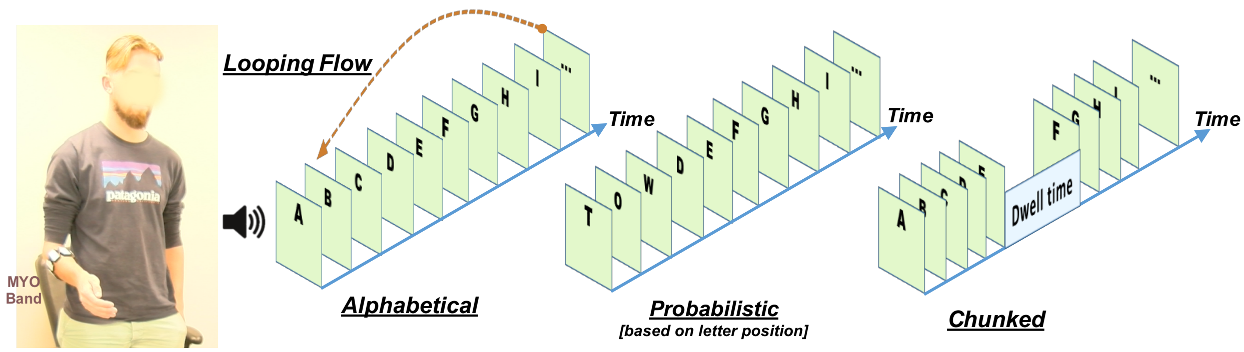


**Figure 1. We investigate novel forms of entirely auditory keyboards that support text interaction without a reference screen. Time, rather than a fixed location in space, becomes the dimension in which to navigate symbols (right); a blind user experiments with an off-the-shelf armband to type in screenless mode (left).**

## ABSTRACT
Accessible onscreen keyboards require people who are blind to keep out their phone at all times to search for visual affordances they cannot see. Is it possible to re-imagine text entry *without a reference screen*? To explore this question, we introduce screenless keyboards as aural flows (keyflows): rapid auditory streams of Text-To-Speech (TTS) characters controllable by hand gestures. In a study, 20 screen-reader users experienced keyflows to perform initial text entry. Typing took inordinately longer than current screen-based keyboards, but most participants preferred screen-free text entry to current methods, especially for short messages on-the-go. We model navigation strategies that participants enacted to aurally browse entirely auditory keyboards and discuss their limitation and benefits for daily access. Our work points to trade-offs in user performance and user experience for situations when blind users may trade typing speed with the benefit of being untethered from the screen.

## Author Keywords
Aural navigation; screen-reader users; accessible text entry.



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## CSS Concepts
• Human-centered computing~Auditory feedback • Human-centered computing~Accessibility

## INTRODUCTION
On-screen keyboards support text entry on mobile devices by displaying a visual layout of letters but continue to pose significant challenges for people who are Blind or Visually-Impaired (BVI). Whereas a person who is blind may walk with some form of travel aid in one hand (cane, a human companion or guide dog), mobile displays force users to coordinate two hands to swipe or touch type on the screen.

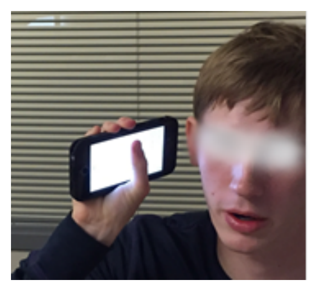

**Figure 2. Smartphones require screen-reader users to stay "glued" to their mobile devices for touch typing (picture from authors' lab).**

The root problem is that visual keypads require such a narrow range of motion and fine-grained manipulation that text entry becomes impractical, especially when a blind person is on the move and needs one hand free to touch nearby objects promptly. Current efforts in eyes-free text entry [1], accessibility standards [2], and mobile typing for the BVI [3] do not fully solve this problem, because they remain screen-centric: accessible keyboards read aloud keys upon touch but ultimately constrain users to hold up a device and slide fingers in search for symbols they cannot see [4]. Whereas voice input is convenient in particular contexts, research increasingly shows that it may come at the high cost of breaking security, social and privacy boundaries [5-8]. As a result (Fig. 2), blind users end up having to hold out a phone at all times when typing, and halting travel altogether to perform quick searches, send a text, or check the next bus transfer.

Is it possible to re-imagine text entry without relying on a reference screen? What would a *screenless* keyboard look like? Would it be even possible to type without a screen? How would users attend to and manipulate characters?

By exploring the above questions, this paper contributes:

- The notion of *keyflow*: a new concept to inform the design of auditory keyboards untethered from a visual display. Keyflows operate as a looping auditory stream of fast-spoken, TTS characters that can be navigated and controlled by a suitable form of screen-free input. Keyflows embody a deterministic, linear approach to text entry that serves as an invisible but audible affordance where characters do not remain trapped in a visual-spatial layout, but flow over time as auditory loops into the user's ears.
- A working system that enables users to interact with keyflows for text entry using an off-the-shelf armband for character selection, and a Bluetooth-connected mobile application that stores and streams the auditory structures. In a *sample typing scenario*, the system enables a user to keep the phone in her pocket and listen to a fast sequence of A-Z characters rendered in TTS (keyflow). Upon hearing the target letter, the user (wearing an off-the-shelf armband) pinches two fingers to select the first symbol, and then listens to a new loop of the keyflow to select the second symbol, and so on (Fig. 1).
- A study with 20 screen-reader users who used keyflows during basic typing tasks, and reported on their experience with navigating for the first time auditory keyboards that do not rely on a visual screen. Our findings show that all participants were able to type in screenless mode. Text entry took much longer than current screen-based affordances (e.g., eyes-free input on QWERTY keyboards) mainly because entry rate is bound to the time-based linear structure of the keyflow. Yet most participants preferred screenless keyboards over voice input and screen-centric methods, especially for short messages on-the-go. Participants exhibited new navigation strategies to aurally browse keyflows and self-reported a positive experience with screenless typing.

Our work contributes to expanding the design space of accessible keyboards by investigating the role of auditory navigation structures in supporting text manipulation without a visual display.

## RELATED WORK

### Accessible Text Interaction on Smartphones

Prior work recognized the need for identifying better typing methods for the blind. NavTap[9] and BrailleTap[9], for instance, remapped the functions of the mobile keypad to navigate the alphabet (or a Braille pattern) with audio feedback, without having to memorize which key to press for a symbol. With the proliferation of smartphones and handheld devices, new methods for audio-based menu navigation emerged, such as Earpod [10] and SlideRule [11]. SlideRule, for example, enabled BVI users to browse objects on a smartphone with audio-based, multi-touch gestures on the screen (e.g., one-finger scan to browse a list; finger tap to select an item). Developed as an iPhone-based system, No Look Notes [12] employs multi-touch input and audio output with a two-stage selection approach. The system divides up the alphabet in a pie menu with seven slices; users first select a slice containing three letters by tapping on the screen, then they select the desired character out of the three proposed. Designed in a similar vein, Escape Keyboards [13] enables users to select letters with one hand by pressing the thumb on different areas of the screen and performing a flick gesture on circular menus with letters. By integrating multimodal feedback, the Multimodal Text Input Touchscreen Keypad (MTITK) [14] partitions the screen in a 4x3 grid that forms the familiar 12-button telephone layout. To codify letters, MTITK employs a combination of finger multi-touch for on-screen input, as well as TTS, auditory icons and tactile vibrations for output. Recent approaches to enable blind users to control mobile screen readers through buttons positioned on the walking cane are designed to help liberate users from having to hold a phone in their hands [15].

### Mobile Typing in Braille

Advancing mobile interaction for Braille users received significant attention [16-18]. Perkinput [1] detects which finger touches the smartphone screen and uses it to provide a nonvisual text-free method based on 6-bit Braille, with one or two hands. BrailleTouch [3, 19], for instance, introduces a keyboard for blind users on smartphones. This keyboard supports one-handed, six-key chorded typing to alleviate the need for touch typing on too-small soft keyboards or using Braille displays that are expensive and cumbersome to carry [14]. TypeInBraille [20] combines braille-chorded keypads with on-screen swipe gestures for typing commands. To decrease two-hand coordination, BrailleType [21] supports single-finger text entry on a smartphone Braille keyboard.

### Mobile Text Entry in Blind Conditions

Eyes-free text entry can benefit all users who cannot look at the screen at all time for temporary, situational impairment [22, 23]. With the Twiddler [24, 25], a mobile device for text entry that fits inside the hand (like a small remote controller), users can type in eyes-busy situations; for example, when in a meeting, having a face-to-face conversation or walking. The device supports chorded input, enabling users to press a few keys simultaneously in coded combinations that generate the desired characters. On-screen mobile keyboard solutions for stroke-based gesture typing have also been developed [26-28] and later commercialized as the Android ShapeWriter. Other approaches, such as the smartphone keyboard extension Minuum [29], shrink and linearize the visual keypad to enable faster touch selection. Most recently, the miniaturization of smart devices, such as wearable watches, has also spurred new interest in pushing the boundaries of typing on small surfaces [30, 31] with results that show the potential of predictive, mini soft keyboards to support people in performing efficient text entry on smartwatches. The state-of-the-art in mobile typing generally assumes the presence of a display to visualize the text and control the selection of characters. By following a trajectory from smartphones to miniaturized and wearable displays, we are seeing first signals of efforts exploring the disappearing of the screen to enable micro-interactions [32] with nimble finger-worn or hand-worn devices.

### Navigating Auditory Menus

Research on navigating auditory displays for Text-To-Speech (TTS) showed the value of employing the outstanding listening ability of the blind when attending to and browsing text. Work on advanced auditory menus [33] and aural browsing of information architectures [34] contributed techniques to augment and speed up access to text-based interfaces for the BVI and to balance the intelligibility of speech output with task efficiency. Spearcons [35], for instance, speed up the TTS output of a sentence to the point that it is almost no longer recognized as speech but still retains intelligibility to enable faster navigation in auditory menus. To support rapid listening to long menus, Spindexes [36] augment fast TTS menus by emphasizing the first letter to provide better orientation. The effectiveness of these approaches rests on the ability of screen-reader users (especially when congenitally blind) to encode auditory text much more efficiently than sighted users [37]. This ability assists them in recognizing text items at speed rates that are unintelligible for non-screen-reader users. Studies on speed rates of TTS indicate that the blind can listen and understand TTS at around 400-500 wpm [38], which is almost three to four times faster than TTS intelligible to first-time listeners. Such a fast listening ability pairs with a memory advantage whereby the blind can perform a higher recall of auditory stimuli in the short term [39]. The findings in this area prompt us to consider text manipulation approaches where BVI can listen to fast TTS and recall letters for rapid selection.

### Indirect Input with Scanning Keyboards

Research on eyes-free text entry operates under the assumption of direct input: users can directly reach the desired letter on a physical surface to select it. An alternative model by *indirect input* received attention in rehabilitation contexts for augmentative communication [40-42] to support users who, due to severe motor impairment, cannot use hands or arms to reach keys. In this situation, users employ a single "selector" to scan a character set and choose the desired one. Such *scanning keyboards* [43] or *single-switch systems* [44] enable typing with "one key" and hold promise in contexts where users cannot afford to hold physical keypads for text entry. An application of this approach is Letterscroll [45]. Here, users can rotate the wheel of the mouse to cursor across a static character set and then use one key to select a letter or symbol. Current scanning keyboards, however, remain screen-bound, thus tethering users to a visual display to control text editing.

Concerning the state-of-the-art in these areas, the novel aspect of our contribution is a *screen-free*, time-based, auditory affordance specifically designed to scan and navigate characters for *text entry*.

## KEYBOARDS AS AURAL FLOWS: KEYFLOWS

*"Space is an order of co-existences. Time is an order of successions". ― G.W. Leibniz [46]*

The fundamental problem of screenless text interaction is that of defining aural structures of the character set (rendered in Text-To-Speech) that are amenable to efficient control and selection. In a traditional, screen-based environment, characters are permanently visible on physical keypads. This paradigm allows users to locate always-available symbols quickly just by glancing at the keyboard. Accessible keypads do read aloud a key upon touching, thereby notifying the user of the possible selection. When we consider an entirely aural setting, however, with no screen available, controlling the character set remains a challenge because the auditory output is *ephemeral*: users hear a symbol just before it disappears in time, and there is no fixed location on the screen to locate it.

To investigate this problem, we propose the notion of <u>key</u>board as aural <u>flow</u> (*keyflow*) as the organizing principle that can assist in defining an entirely aural character set, so moving it from the visual-spatial order to audible prompts over time. *A keyflow is a looping auditory stream of fast-spoken, TTS characters arranged by a convenient time-based layout, and controllable by a suitable form of screen-free input.* Keyflows act as an invisible but audible keyboard where characters do not remain trapped in a visual-spatial layout to be searched for, but they flow over time as auditory loops into the user's ears. At its core, the concept of keyflow entails three main components: (1) a usable sequential arrangement and speed of the aural character set as *output*; (2) a form of screen-free *input* (e.g., a wearable) for navigating, controlling and selecting characters; (3) a mobile application that stores the character sets, serves the TTS output, and receives commands from the input device (Fig. 3).

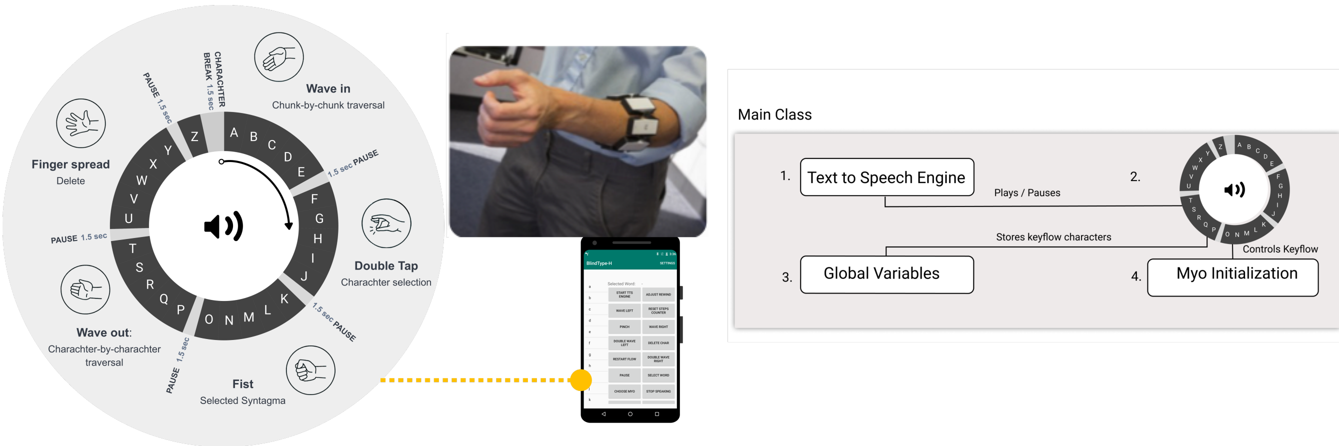


**Figure 3. Keyflow interactions (left) and basic architecture (right). As a first manifestation of input, we used the Myo armband to support five gestures that enable users to: navigate back and forth, select characters, and read/delete the typed letters.**

## Keyflow Design Space

### *Aural Layouts for the Spoken Character Set*

We iteratively explored and prototyped alternative keyflow layouts thanks to the feedback and ideas of both blind and sighted researchers in our lab. For example, we experimented with two arrangements of characters: *probabilistic* and *alphabetical*. The *probabilistic* layout speaks letters sequenced according to the decreasing probability of occurrence for each selection, based on available statistics on English linguistic corpora [47]. The first keyflow starts with the letters that are most probable (statistically speaking) to be the first letter of a word. Upon selection, a second keyflow kicks in starting with letters with the highest probability to be in the second position in the English language, and so on. The *alphabetical* layout reads letters in A through Z order, with characters starting from A after every selection. In an early pilot session with two blind participants who were not part of the research team, we let them use both aural layouts for composing simple words and discussed with them their experience. Their feedback was consistent and clear. Probabilistic keyflows, although theoretically more efficient, caused much confusion, because users did not know what to expect at any given time. This layout created unnecessary mental fatigue, lack of sense of control over the aural character set, difficulty in attending to letters, and delays in reaction time to select a letter. On the contrary, the alphabetical layout proved to be much more usable, controllable and predictable, and thus amenable to more accurate selection, even if users had to wait for frequently-needed letters at the end of the alphabet sequence.

### *Speed and Time Constraints*

It became apparent during the initial design that *time* plays a crucial role in structuring entirely auditory keyboards. Keyflows bound the user experience to time by four basic constraints: (1) the speed (number of characters spoken per second); (2) the time a user takes to recognize a spoken letter; (3) the time a user takes to react to the recognition through motor input; (4) the time the input technology takes to recognize and execute the input on the keyflow. Based on feedback from blind participants on pilot prototypes, we settled on a speed of *two characters per second*. We observed that this rate enables the flow to progress rapidly and preserves quite well the intelligibility of the letters.

### *Control and Chunk-Based Navigation*

With the help of one blind researcher, we explored features that could improve user control and navigation. For example, because the stream of characters plays automatically in a loop, users have the opportunity to re-find letters that they might have missed just by waiting. Users indicated that they wanted a mechanism to remain more in control of the keyflow at all times by having the opportunity to “skip ahead” when needed. Based on this input, after iterative trials, we introduced the possibility not only of scanning the keyflow manually, but also to skip “chunks” of five symbols to arrive faster to a target letter. Between every chunk, we introduced a brief pause (“dwell period”) of 1.5s to make it easier for users to manage the letter stream (Fig. 3). We expected chunking to mitigate the ephemeral nature of the keyflow by forming rapid bursts of five characters processable by short-term memory.

### *Time-Based Symbol Selection with Delay Off-Set*

Given the dynamic nature of the auditory stream, by the time the user recognizes the desired letter, the keyflow has already moved past that letter. Because of the limits of human cognitive and motor ability, we have observed early on in our work that such an inevitable delay between the recognition and motor selection causes users to enter the wrong character. To increase the chance of accurate selection over a character set fluctuating over time, we have iteratively designed and validated instantaneous off-set mechanisms that “rewinds” the keyflow by the time interval of the expected delay. Based on our preliminary evaluation with both sighted and blind participants, we have settled on *two-character* rewind for the A-Z layout.

| ID | Gender | Age | Visual Impairment/Other disability | Devices used to type |
|---|---|---|---|---|
| **1** | Male | 45-50 | Blind with **some** light perception | Voiceover on iPhone, dictate feature |
| **2** | Female | 45-50 | Blind with **minimal** light perception | Voiceover keyboard |
| **3** | Male | 25-30 | Blind with **some** light perception | Voiceover on iPhone, Dictate feature |
| **4** | Female | 25-30 | Blind with **some** light/color perception, short-term memory loss | Dictate feature: essentially Siri, Voiceover on iPhone |
| **5** | Female | 45-50 | Blind in one eye and extremely low vision in the other | A sighted person helps P5 to type; Sometimes she uses the Dictate feature and Voiceover on iPhone to type |
| **6** | Female | 30-35 | Blind with **minimal** light perception, Dyslexia | Dictate feature: essentially Siri, Voiceover on iPhone |
| **7** | Female | 45-50 | Blind with **minimal** light perception | Voiceover on iPhone |
| **8** | Male | 30-35 | Blind with **minimal** light perception | Dictate feature: essentially Siri, Rarely voiceover on iPhone |
| **9** | Male | 30-35 | Blind in one eye with **some** light and color perception, extremely low vision in the other | Dictate feature: essentially Siri, Flicktype |
| **10** | Male | 40-45 | Blind with **minimal** light perception | Voiceover on iPhone |
| **11** | Male | 60-65 | Blind with **some** light perception | Voiceover on iPhone |
| **12** | Female | 50-55 | Blind with **some** light perception | Dictate feature, Voiceover on iPhone |
| **13** | Female | 45-50 | Blind with **minimal** light perception | Dictate feature: essentially Siri, Voiceover on iPhone |
| **14** | Male | 65-70 | Blind with **minimal** light perception | Dictate feature, Voiceover on iPhone, Talkback on Android |
| **15** | Male | 55-60 | Blind with **some** light/color perception | Talkback on Android |
| **16** | Male | 40-45 | Blind with **some** light/color perception in one eye and **some** vision in the other eye | Talkback on Android |
| **17** | Male | 40-45 | Blind with **some** light/color perception | Dictate feature, Voiceover on iPhone |
| **18** | Female | 40-45 | Blind with **minimal** light perception | Talkback on Android (old phone) |
| **19** | Male | 50-55 | Blind with **some** light/color perception | Flip phone |
| **20** | Male | 50-55 | Extremely low vision, on a wheelchair | Dictate feature, Talkback on Android (old phone) |

**Table 1. Demographics of study participants.**

### Architecture and Gesture Input

To support in-air input, building on related work [48], we chose to prototype the gesture input with the MYO armband [49], a gesture control armband worn just below the elbow of the dominant hand. The device tracks the hand gestures made by the user and directly communicates the interactions to the android application. The technical set-up we used includes an Android system, studio version 3.1.0, and a Google Nexus model LG-H791 equipped with an Android 8.0.0 (Lollipop). Although the MYO can recognize several gestures, based on iterative evaluations in the lab, we settled on using only five basic gestures to control the keyflow (See Fig. 3): (1) *Double tap* for selecting a character; (2) *Wave-in* to skip chunks ahead of the keyflow; (3) *Wave-out* to backtrack letter-by-letter; (4) *Fingers spread* to delete the latest character; and (5) *fist* to read out the typed letters at any time. The codebase of our system is available at https://iu.box.com/v/iupuikeyflows.

## STUDY METHODS

The goal of our IRB-approved user study was to investigate the user experience and performance of people who are blind during their first exposure to keyflows. Specifically, we were interested in gauging their navigation behavior in controlling a screen-free, entirely auditory keyboard, and understand the limits and potential of this approach to enhance the accessibility of typing.

### Participants

We recruited 20 participants (Table 1) from a Midwest-based non-profit organization (BOSMA Enterprises), which provides training programs that assist individuals in overcoming barriers of blindness and visual impairment. Among the 20 participants (13 male and 7 female), 18 identified as blind with minimal or some light perception; one identified as blind in one eye and low vision in the other; and one had extremely low vision. Participants had varied expertise in smartphone-based assistive technologies; all but one frequently used screen readers and accessibility features on their smartphones. Many participants have experienced degeneration of their visual abilities due to unforeseen medical conditions, age-related congenital eye conditions, muscular degeneration, diabetic neuropathy, short-term memory loss or autism.

### Procedure

Using a mixed-method approach, we conducted a semi-structured user experience and performance evaluation at BOSMA with each participant. We set up a video camera on a tripod and recorded each session with the participant's consent. One moderator interacted and guided the participants through the study, while two researchers were co-present and took notes throughout each session.

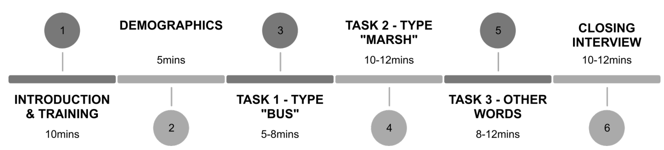


**Figure 4. Synopsis of the study procedure.**

Each session comprises of three main parts (Fig. 4). We started with a brief study introduction and training on the concept and mechanics of typing with entirely auditory keyboards, including the organization of the characters and the MYO-supported gestures for navigation and control. Then, we presented users with a scenario and asked to type the words BUS (searching for the nearest bus stop) and MARSH (locating a local grocery store); if time permitted, participants were also asked to try out to type any other word they would like. After the session, we verbally gauged from participants the perceived level of difficulty, mental and physical demand on a 5-point Likert Scale. Finally, through open-ended questions, we asked them to reflect and share any comments regarding issues, challenges, potential usage, and benefits of keyflows based on their experience. For approximately one hour and fifteen minutes of participation, each participant received a $50 gift card.

### Analysis

We conducted both a quantitative and qualitative analysis of the videos and notes collected to characterize as accurately as possible key dimensions of the user performance and experience. We analyzed quantitative user performance data and nominal responses to the Likert-scale questions with descriptive statistics. We conducted a qualitative analysis of the user's responses to the perceived usability questions and open-ended questions. Four researchers iteratively contrasted and compared the data to identify themes emerging from the experiential responses.

## RESULTS

### User Performance

14 of the 20 participants were able to type at least one full word in screenless mode. These included BUS, MARSH, or any other word of their choice. Based on the number of words typed by these 20 BVI participants, we have organized user performance in six groups (Table 3).

*Task 1: Typing "BUS"*

Combining groups G1, G2, G3 and G5, 10 out of 20 participants typed the word BUS by taking an average time of 1 minute 23 seconds with a standard error of 31.62%. The average time to type individual letters of the word BUS is 31.4 seconds (B), 24.8 seconds (U) and 27.6 seconds (S). The difference in typing performance for each symbol was due to a variety of user and system factors that we observed during the sessions. For example, users who became quickly familiar with keyflows, like P13, tried to land on U faster by quickly *waving-in* to skip chunks ahead. However, this resulted in P13 accidentally skipping the chunk containing the desired letter due to performing the gesture three times in a row. When P13 did get to the right chunk, a miss-selection of characters occurred due to the selection of V instead of U; he then was able to delete V and select U.

*Task 2: Typing "MARSH"*

Combining G2 and G5, only 3 out of 20 participants were able to type the word MARSH, taking an average time of 2 minutes 4 seconds with a standard error of 57%. The average time taken to type individual letters is very long: 18 seconds for A, 17.33 seconds for R, 14.66 for S, and 13.66 for H. The average time taken to type M (60.6sec) is skewed by the exceptionally long time taken by P13 to type M (123sec) in contrast to P14 (38s) and P19 (38sec). This participant attempted different gestures and skipped chunks multiple times to get to M faster. Invariably, she skipped the chunk containing M three times.

| Group | Description | Participants | |
|---|---|---|---|
| G0 | Participants were able to type one letter only or were unable to type any other letter | P1, P4, P5, P16, P17, P18 | #6 |
| G1 | Participants were able to type the word "BUS" only | P8 P11 P15 P20 | #4 |
| G2 | Participants were able to type the words "BUS" and "MARSH" only | P13 P14 | #2 |
| G3 | Participants were able to type "BUS" but failed to type "MARSH" and typed other words | P6 P7 P12 | #3 |
| G4 | Participants failed to type the word "BUS" and "MARSH" but typed other words | P2 P3 P9 P10 | #4 |
| G5 | Participants were able to type the words "BUS," "MARSH" and other words as well | P19 | #1 |

**Table 2. Performance Groups.**

*Modelling User and System Errors*

The sequential and deterministic nature of the letter arrangement significantly slowed down typing, because participants had to first listen to symbols being read for selecting them. Also, different types of errors negatively impacted the user performance. These included: inaccuracy in performing hand gestures; gesture confusion (wrong gesture selected); gestures misrecognized by the armband; wrong character selection; and system errors. See Table 3 for a tabulation of the error types, ordered by decreasing number of occurrences across participants. Insights emerged during the closing interview helped explain the nature of some the errors. For example, one participant explained unrecognized gestures as follows:

> "*I have a muscular degeneration, and because of that, my muscles are weak on my arm. The gestures that I am performing are not being detected for this reason*" – *P14*

Five participants (25% of the sample) shared during the discussion that they had additional health conditions or disabilities (e.g., Autism, short term memory loss, muscular degeneration, Dyslexia, Diabetic neuropathy) that impacted their timely interactions with keyflows. For example, the difficulty to recall a letter in short-term memory or learn which gestures to activate played a critical role in the user performance for five participants:

> "*I have short term memory loss; I had a very bad accident. There is still some of the [stuff] that I might forget*" – *P4*

## NAVIGATION STRATEGIES FOR TARGET ACQUISITION

Keyflows serially disclose spoken characters in a rapid looping progression. As such, they represent an affordance for text entry that users never encountered before. When coping with the time-based structure of the character sets, participants exhibited three primary navigation behaviors to reach a target letter for selection: (1) *listening and waiting* for the target character; (2) *proactively skipping* chunks and then fine-tuning their approximation to the target; and 3) *retracing* characters.

| Error Type | Definition | Example | Total # of Participants Affected | Error Occurrences per Participant | | | |
|---|---|---|---|---|---|---|---|
| | | | | Min | Max | μ | δ |
| **Unrecognized Gestures** | Gestures are not recognized | When a Wave-in gesture is performed, and the chunks are not skipped | 19 | P18 (2) | P12 (28) | 9.05 | 5.86 |
| **Wrong Character Selection** | The system selects a wrong character | 'S' selected when the double-tap gesture was performed at 'R,' 'Y' gets selected automatically | 19 | P7 & P16 (1) | P2 (23) | 8.11 | 5.43 |
| **Gesture Misrecognition** | A different gesture is executed | When a double-tap is performed, the prototype recognizes a wave-in gesture | 18 | P4, P6 & P18 (4) | P10 (15) | 8.83 | 3.73 |
| **Gesture Precision** | Participants had difficulty in performing gestures accurately | A double-tap gesture is executed on 'Q' when 'R' needs to be selected; arm not at a right angle to the shoulder | 13 | P9 (1) | P12 & P13 (13) | 6.33 | 3.58 |
| **Gesture Confusion** | Users get confused among gestures and their functionality | A wave-out gesture is performed instead of a wave-in | 12 | P13 & P20 (1) | P14 (6) | 2.41 | 1.31 |
| **System Errors** | Problems related to the prototype | System stops; Synchronization issues; need to reboot. | 9 | P2, P4 & P15 (1) | P14 (4) | 2.11 | 1.05 |

**Table 3. Types and Volume of Errors that Affected User Performance.**

### Listening and Waiting for the Target Character

Three users (P3, P16, and P19) consistently approached aural navigation by attentively listening to the keyflow, mentally following the alphabetical sequence being read, and patiently waiting for the character to arrive. However, as the target character was read aloud (e.g., M), they would intentionally let it pass, and thus continue to listen to the keyflow (see Fig. 5). As the second keyflow loop starts, they would follow it to the target letter, then select it upon hearing it for the second time. In an example from our video analysis, while M could have been selected in 10 seconds, the total time for target acquisition ended up being 32.5 seconds.

Based on our observations and discussion with participants, we attributed this behavior to three potential sources. First, these users at the beginning preferred to familiarize and to get comfortable with the interaction mechanism, to explore the keyflow behavior, and to get a feel of this new organization of the characters.

Second, due to inadvertent muscle movements of these participants, the system at times failed to track the users' attempt to skip chunks, and so they preferred, conservatively, to wait for the desired letter. Third, some letters (e.g., "B" in BUS) arrived too early in the sequence (being position at the beginning of the alphabet). Although the alphabetical sequence was predictable, the "too early arrival" of a character did not give enough time to the user to catch it on the first loop.

In this case, for example, B arrived after 1.5 seconds the keyflow started, but participants let one loop go by and were able to select it after 23.25 seconds.

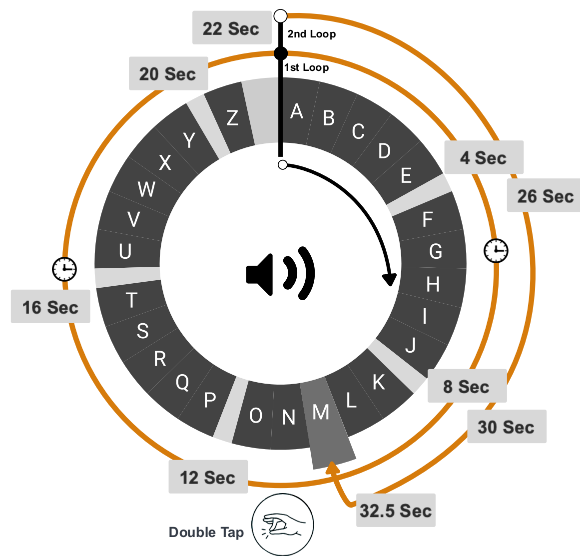


**Figure 5. While waiting for the target (M), some users preferred to let the flow run one loop before selection.**

### Skipping Chunks and Fine Tuning

13 of the 20 participants (P1, P2, P4, P5, P6, P7, P11, P12, P13, P15, P17, P18, P20) showed the following navigation behavior consistently: they skipped letters by chunks and resumed listening letter by letter upon hitting the *beginning of the chunk they assumed contained or was close to the target letter*.

For example (Fig. 6), when U was the target, users skipped the first three chunks (A-E; F-J; K-O). As soon as the keyflow read the letter P, they let the keyflow run its course until the letter U (at the beginning of the next chunk) and then selected it. This navigational behavior enabled these users to select letters accurately and faster than those who let the keyflow run letter by letter from the beginning.

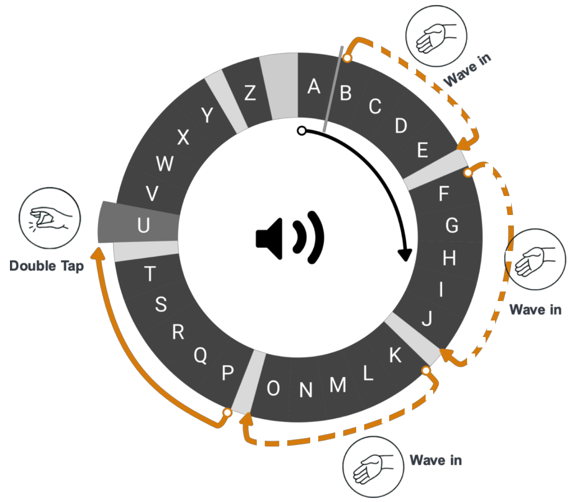


**Figure 6. Most participants (13) engaged in skipping flow chunks (of 5 letter each) to reach the target (U) more rapidly.**

### Retracing Characters

Four participants (P8, P9, P10, and P14) preferred to let the keyflow go past the target character by only three to four positions and then *backtrack letter-by-letter* to the target. This navigation strategy (Fig. 7) was also used as an alternative to solve the problem of missing characters when they arrive too early in the flow. Participants mentioned that selecting the first three letters (A, B, and C) is difficult because the keyflow begins with these letters, which inadvertently and too quickly go by.

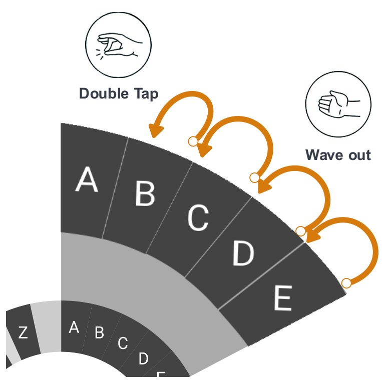


**Figure 7. Four participants frequently navigated backward the keyflow letter-by-letter to retrace a missed character.**

For example, to select B in BUS, these participants preferred to let the keyflow go until E and then "wave out" letter-by-letter from E to D to C to the target B.

### Self-reported User Experience

When reflecting on their experience, participants verbally self-reported very positive scores of perceived ease of typing tasks, physical demand, and mental demand. Notwithstanding the fact that typing letters in screenless mode took a long time and asked them to adapt to new interaction and navigation behaviors, their overall response indicate low levels of perceived physical and mental demand as well as a general ease in performing the tasks, with average scores below 3 on a 1 to 5 scale (Fig. 8).

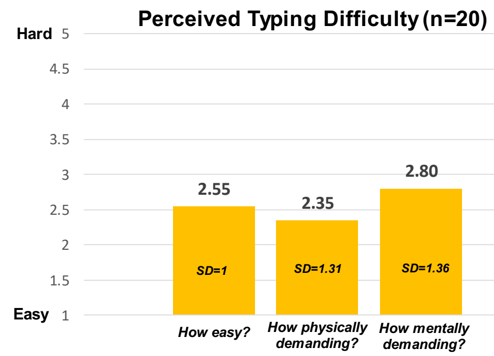


**Figure 8. Users rated on a 1-5 scale their perceived ease of use, physical and mental demand of screenless typing.**

When asked about the advantages and limitations of keyflows to support typing tasks, participants offered a broad array of insights, presented in what follows.

#### *Typing short messages on-the-go*

Fourteen participants mentioned that they would use the keyflow outdoors while simultaneously using a cane or a guide dog. These participants remarked that it gets very challenging for people who have both a guide dog and a cane to type on their phone. P3 mentions that he uses different kinds of keyboards for various purposes and that he would use auditory keyboards to send short messages to communicate with others while navigating outdoors with a guide dog. P11 pointed out that the primary factor when navigating outdoors is the collection of familiar sounds they hear. These sounds are essential cues for people who are blind to learn about their location and navigate outdoors. Continually listening to the stream of letters might be a distraction for users navigating outdoors. As such, P11 would use the keyflow to type short one-word messages or brief phrases instead of long textual details.

> *"While walking and using a cane, the user needs to hear all the sounds around and be aware of the surroundings. Hearing the keyflow will only be used for smaller tasks rather than full-fledged tasks"* – *P11*

P16 confirmed this perspective and proposed an idea. Considering the rapid advancement of wearable technologies, P16 would prefer to use only one earbud (of the two typically available) to use the keyflow. In his experience, this method would enable him to equally concentrate on the letters on one ear and the surrounding natural sounds on the other. P10 was more critical of the concept and mentioned that this auditory keyboard would slow down the process of typing lengthy messages. Whereas P10 would prefer an accessible keyboard attached to a desktop computer to type long and detailed messages, he also found potential in using the keyflow to type short instant messages and short emails.

#### *The convenience of keeping the phone out of sight*

Participants indicated that they would like to use the keyflow both indoors and outdoors. In this way, they could keep the phone away and be able to type hands-free, especially while running errands and performing daily household chores. P6 and P13 suggested that screenless typing would be useful to text family and friends while being busy with little kids at home.

> *"Keyflows can be used while multitasking and I can focus on where my kids are in the house and try to get them to do what they are supposed to be doing"– P6*

> *"When you're out in public, you are already juggling with your phone, cane, computer and if my kid texts me it's hard to hear, but with this I can listen while I am walking in the hallway and I don't have to try to juggle to get my phone out; that would be very helpful" – P13*

P7 shared that once a cab driver stole her phone while she was busy collecting her belongings. Because of this experience, P7 indicated that with screenless typing her accessible devices and phones could remain safe. P10 corroborated this point:

> *"It is fluid and intriguing; I like it. It is a good concept, good to use without taking out the phone" – P10*

#### *Integration with other services*

Participants suggested that entirely auditory keyboards could be integrated with other applications where typing is crucial, such as Lyft, Uber and Facebook Messenger. People who are blind or visually impaired often find it challenging to type the exact location and order a ride. P5 believes that the auditory keyboard would be extremely beneficial for this purpose. Users could request a ride by using hand gestures to input short words or letters (e.g., current location and destination initials).

> *"This auditory keyboard could be used with Lyft and is ideal if perfected" – P5*

P4 also suggested that keyflows could be applied to desktop devices and big screens like interactive kiosks in malls or smart TV's at home to input data. When reflecting on a broader application scope, some participants expressed their desire to use keyflow to be able to control an entire device (e.g., Android or iOS smartphones), just like screen readers do for webpages and applications. P10 mentioned that it would be interesting if he could control his smartphone directly through hand gestures for tasks like powering his phone on and off and toggling among various applications.

#### *Keyflows versus other typing methods*

14 of the 20 participants indicated that keyflows are a better form of typing compared to voice input. For example, P13 remarked that using voice to type sensitive information is challenging. Because people with visual impairments are not always aware of their surroundings, important information could be easily leaked around.

> *"While the reaction time is a major factor, the auditory keyboard could be quicker than the current methods of typing" – P13*

> *"I think this will be better than the normal methods" – P15*

P13 commented that the keyflow is a quicker method to type hands-free when compared to Voiceover, Talkback, Flicktype or speech-to-text formats. In her view, the critical factor that determined her performance was the reaction time: the time between hearing the desired character and the prompt reaction needed to act and select. For P13, getting trained to the short reaction time is essential; it would allow users to select letters promptly and speed up typing.

> *"If everything did work, it could be beneficial for people who have difficulty with virtual keyboards" – P7*

Two participants (P10, P18) suggested to integrate an option to "adjust the speed" of the keyflow (like in screen readers), and this could help reduce inaccurate selections:

> *"I would like to have it slower so that I can get all the gestures and then speed up as that's how I did with the voiceover on my phone which started at about 40 and now I am at 85-90" – P10*

> *"I would like to slow it down a little bit, but I know eventually my speed will be there so then I would like to readjust it" – P18*

Traditional typing methods using Talkback or VoiceOver systems require visually impaired people to use both hands to type. P16 believes that the keyflow could help remove this dependency and screenless typing could also assist people who are *one-handed* to type more comfortably.

> *"People with one hand could still be able to type without really reaching for the phone" – P16*

#### *Experience Breakdowns and Pain Points*

An issue that participants noted is the lack of immediate and appropriate feedback when performing gestures. For example, some participants expected the prototype to let them know whether a gesture was successfully executed or not, and expressed frustration for frequent misrecognition:

> *"Swiping on the phone is easier as it gives feedback and I am in control while typing at my own pace" – P1*

> *"I might just get frustrated (with the armband) while typing and be like oh my gosh, I am just going to use my phone" – P4*

When commenting on their experience with the armband, P12 remarked that any new device adds to the burden of items to carry around (cane, smartphone, or a guide dog).

> *"I need to remember an extra thing to carry" – P12*

## DISCUSSIONS AND FUTURE WORK

### Aurally Browsing a Time-Based Paradigm and Syntagm

The composition of language advances along two dimensions: (1) the *paradigm* (the space of the selectable symbols), and (2) the *syntagm* (the sequence of the selected symbols, brought together by grammar rules). On-screen keyboards visually and spatially embody this distinction: the visible keyboard visually represents the paradigm, while the typed text represents the ongoing syntagm. By enabling screen-free, entirely auditory typing, keyflows extend the notion of keyboard by moving it from a *location in space* to the *dimension of time*: the *paradigm* becomes a looping aural stream of rapidly spoken, selectable characters, whereas the *syntagm* is the set of typed letters read on demand. The findings on the user performance and experience suggest that this transition from space to time is currently not an easy one: a vital trade-off to consider is the loss in efficiency in order to gain a screen-free experience.

### Untethered from the Screen but Bound to Time

The user performance showed that participants took a very long time typing letters. This phenomenon was due to a variety of factors that we modeled as different kinds of errors (e.g., frequent armband misrecognition), but also to the linear structure of the keyflow, which binds users to listen to a stream of characters for control and selection. In order to liberate users from a continuous tethering to the screen, keyflows tether users to the dimension of time. Even when equipped with techniques to skip chunks of letters, users are tied to the serial nature of the keyboard. Participants responded to this trade-off by appreciating the notion of screen-less and phone-less interaction as potentially benefiting their daily life. Their feedback indicated that they prefer typing short messages in screen-free mode than with current screen-centric methods. Positive user feedback emerged even though the current limitations of the prototype (both in technical execution and time-based navigation) significantly slowed down their tasks. Given the constraints imposed by a deterministic, time-base structure, we envisioned keyflows to be used where other screen-based methods fail and for "initial" letter typing. For example, existing auto-completion techniques may kick in after two or three characters are typed, and a keyflow with suggested words would play for selection. Navigation alternatives should also be explored to make the keyflow more error-tolerant. This could be done by increasing the level of directed scanning and granular control on the keyflow navigation in line with studies on web navigability with screen readers [50-52].

### Limitations of Input Devices

The use of the off-the-shelf armband revealed pain points for users, mainly due to the gesture misrecognition of the individual and hard-to-control variations of muscular movements. Although our work focused on the aural navigation structure, we recognize that a more reliable in-air input device is crucial for fluid tasks. By operating at an appropriate level of abstraction, the keyflow properties could work with future forms of nimble input such as smart rings [53] and finger-worn devices [54-56]. Experimenting with more responsive input will open opportunities to tighten the user's control over the keyflow navigation and better prevent or recover from errors.

### Modeling Aural Cursor Displacements

When navigating over the keyflow, participants benefited from the automatic two-character rewind to offset the delay between letter recognition and motor selection. Yet more can be done. We have discussed with participants opportunities for users to customize the degree of instantaneous *rewind*, which may depend on the keyflow speed and the user's habituation to the aural rhythm. Such strategy aligns well to the practice of screen-reader users to adjust the TTS rate. Investigating techniques for appropriate aural cursor displacement over entirely auditory keyboards opens a new line of research in *error prevention for screen-free text manipulation*. For example, whereas the body of work on text entry has primarily focused on typing errors in *space* over visual keypads (e.g., selecting an adjacent key rather than the intended one), addressing errors with auditory structures will open opportunities to study corrective selection strategies that operate *over time*.

### Beyond Letters

A comprehensive auditory keyboard needs to provide access also to *numbers*, *symbols* or *special characters*. Further developments may include keyflows with aural arrangements of numbers (0-9) in looping sequence, as well as auditory emoticons to support rapid expressions during screenless texting. Designing suitable navigation mechanisms to move from one type of keyflow to the other open additional opportunities to further investigate the intricacies of future screen-free experiences.

## LIMITATIONS AND CONCLUSION

In this paper, we introduced *keyflows*, a concept for entirely auditory keyboards that do not rely on a reference screen and can complement existing typing affordances for people who are blind. We conducted a study that examined for the first time the user performance and experience with keyflows, and characterized the navigation strategies users employed to interact with characters set serially disclosing over time. Users took a long time to type due to both the deterministic, time-bound nature of the keyboard and gesture recognition errors but found beneficial to type in a mode that is untethered from a screen. Combining keyflows with more reliable and nimble wearables will provide opportunities to support a more efficient and fluid screenless experience. Among the limitations of the work, because of the inherent recognition problems of the armband, this exploratory study was designed and executed in-the-lab to model in a controlled setting the aural navigation mechanics enabled by keyflows. A follow-up work may include a comparative evaluation of text-entry tasks in different mobile scenarios between keyflows and existing techniques (e.g., VoiceOver).


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