DigiTaps: Eyes-Free Number Entry on Touchscreens with Minimal Audio Feedback

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ABSTRACT
Eyes-free input usually relies on audio feedback that can be difficult to hear in noisy environments. We present *DigiTaps*, an eyes-free number entry method for touchscreen devices that requires little auditory attention. To enter a digit, users tap or swipe anywhere on the screen with one, two, or three fingers. The 10 digits are encoded by combinations of these gestures that relate to the digits' semantics. For example, the digit 2 is input with a 2-finger tap. We conducted a longitudinal evaluation with 16 people and found that DigiTaps with no audio feedback was faster but less accurate than with audio feedback after every input. Throughout the study, participants entered numbers with no audio feedback at an average rate of 0.87 characters per second, with an uncorrected error rate of 5.63%.

Author Keywords
Eyes-free text entry, blind, touchscreen, mobile devices.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User interfaces — Input devices and strategies. K.4.2. Computers and society: Social issues – assistive technologies for persons with disabilities.

1. INTRODUCTION
Touchscreens are accessible to blind people with screen readers like Apple's VoiceOver [1], which provide continuous audio feedback to guide a user's interaction. To find a virtual button, for example, the user moves her finger across the screen as VoiceOver speaks descriptions of touched UI elements. Then, to press the button, the user performs a second gesture such as a double-tap. In addition to VoiceOver, researchers have proposed many other eyes-free interaction techniques [2,6,7,13,19,20], which also heavily rely on audio feedback.

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Figure 1. A blind person enters numbers with DigiTaps. The white circles at the bottom of the screen mark her touch points.

Eyes-free methods that require the user's auditory attention can be difficult to use in noisy environments like a street corner, or quiet environments like a library where playing sounds is inappropriate. One can wear headphones to address these problems, but blind people often feel that headphones are clumsy and unsafe. Headphones can block sounds a blind person uses to perceive her environment, such as obstacles in one's path and traffic [3,25,27].

We introduce eyes-free interaction with *minimal audio feedbac*k that enables blind users to interact with a device with little to no auditory attention. In prior work, we developed minimal-audio methods for conveying directions for a wayfinding application that used only a touchscreen and vibration [2]. In the current paper, we explore eyes-free number input with minimal audio feedback. To our knowledge, we are the first to investigate eyes-free interaction with minimal audio feedback for blind people.

We present *DigiTaps*, an eyes-free number entry method with minimal audio feedback for touchscreen devices. DigiTaps can potentially be used in a variety of contexts: when making phone calls, interacting with automated voicemail systems, entering addresses in GPS-based applications, and entering personal identification numbers (PIN). To enter a number with DigiTaps, a user taps or swipes the screen with one or more fingers (e.g., a two-finger tap, a one-finger swipe), as shown in Figure 1. The DigiTaps gestures "feel" different, so people can discern whether they touched the screen with one finger or two. A user performs one to three gestures to enter a digit, according to a code that is derived from the semantics of the digits.

We evaluated DigiTaps as an eyes-free, minimal-audio input method in a longitudinal study with 16 people (six blind, ten sighted). Participants entered sets of digits with and without audio feedback. We found that removing audio feedback produced significantly higher entry rates, but also higher error rates. Participants entered digits at a mean rate of 0.87 characters per second (CPS) (SD = 0.32) with no audio feedback, and a mean uncorrected error rate of 5.6% (SD = 14.8). This seems much faster than VoiceOver, as we found in prior work that participants entered four-digit PINs in 7.5 seconds (about 0.53 CPS) [5].

In summary, our contributions include the design and evaluation of DigiTaps, a novel method for nonvisual number input with minimal audio feedback.

RELATED WORK

Eyes-free input has received much attention from the human-computer interaction community. Recent work has focused mostly on making touchscreens accessible to blind people, relying heavily on text-to-speech. By contrast, DigiTaps was designed and evaluated to support eyes-free entry with minimal audio feedback.

Tap2Count [11], a number input method by Hesselman et al., is a number entry method on large surfaces. Like DigiTaps, Tap2Count gestures relate to the digits semantics and seems appropriate for eyes-free entry with minimal audio feedback. To enter a digit with Tap2Count, a user touches the screen with the number of fingers of the input digit (two hands may be required). DigiTaps is better suited for a small screen than Tap2Count, where the user may be unable to touch the screen with more than 3 fingers.

The *de facto* standard eyes-free text entry method for smartphones is Apple's VoiceOver screen reader [1], which has interaction techniques that were first presented in Kane et al.'s Slide Rule [13]. Android devices have a similar screen reader called TalkBack [10]. There are no official estimates, but it is evident that VoiceOver has been broadly adopted by blind people. VoiceOver enables a user to explore the screen speaking the labels of UI elements that are being touched. To make a selection, a user performs a second gesture: a double-tap or split-tap (touching a second finger to the screen). One must listen carefully when searching for buttons on the screen, which can be especially difficult when selecting one of many small keys on the on-screen keyboard. In prior work, we found that blind people entered text with VoiceOver at a rate of just 4.5 words per minute [4]. Other work confirms that text entry is arduous and error-prone [4,6,21].

Several eyes-free systems have been proposed for blind people to address the difficulty of text entry with VoiceOver [2,5,6,7,19,20]. For example, Bonner et al [6] designed No-Look Notes, an eyes-free keyboard with larger targets, where two button presses are required to enter one character. They found that entry rates with No-Look Notes were still low, at 1.32 words per minute (WPM). Azenkot et al [2], Frey et al [7], and Oliveira [20,21], proposed eyes-free techniques for blind people based on Braille. Azenkot et al's Perkinput and Frey et al's BrailleTouch use multi-finger touches similar to those we use in DigiTaps. However, DigiTaps gestures can be performed anywhere on the screen with no need for calibration [2]. Also unlike DigiTaps, Braille-based approaches require knowledge of Braille dot patterns.

Researchers have also explored eyes-free input for sighted people [7,17,23]. Lyon et al. found that removing visual feedback did not adversely affect text entry with the chording Twiddler keyboard [15]. While the Twiddler has physical keys, the efficiency of chording input inspired the DigiTaps gestures. MacKenzie et al. [16] also developed and evaluated an eyes-free, base-4 text entry method using a joystick called H4-Writer. Like DigiTaps, H4 writer uses prefix-free codes to represent characters efficiently, but it is probably more difficult to learn than DigiTaps because its codes do not relate to the semantics of the inputs.

Graffiti and Unistroke [9] are gesture-based text entry methods that resemble printed characters and are potential eyes-free input methods with minimal audio feedback. While they are efficient for sighted people [28], they are not appropriate for blind people who may not know what printed letters look like [14]. DigiTaps gestures require no knowledge of printed characters.

THE DESIGN OF DIGITAPS

The discussion in the previous section leads us to four design goals for numeric entry. We strive to develop a method that is (1) eyes-free, (2) minimal-audio while being (3) efficient and (4) learnable. Efficiency and learnability are important for widespread adoption.

DigiTaps Gestures

To enter a digit with DigiTaps, a user performs one, two, or three gestures anywhere on the screen. The gestures used for digit entry are a one-finger swipe, a one-finger tap, a two-finger tap, and a three-finger tap. A BACKSPACE is entered with a 2-finger swipe. Swipes can be oriented in any direction.

During our formative studies, we considered using a four-finger tap. It was difficult for people to touch a surface with four fingers simultaneously, however, because the smallest finger, the "pinky," was typically much shorter than the other three fingers. Also, some people could not easily fit four fingers on a phone's screen, so we decided to use gestures that involved up to three fingers at a time.

DigiTaps Codes

After designing the DigiTaps gestures, our goal was to create a code that uses just four symbols to represent 10 digits. Usually, we use 10 symbols, the standard digits 0–9, to encode numbers using place values. One possible way to encode 10 digits with four gestures is to use base-4 notation. The 10 digits would be represented by 0, 1, 2, 3, 10, 11, 12, 13, 20, 21, respectively. This encoding could be difficult to learn, however. Can people quickly learn that the digit 5, for example, is represented by 11 in base-4? Furthermore, there is ambiguity in this encoding: if the digit 1 is represented by a one-finger tap, how would the system distinguish the entry of digit 5, input with two one-finger taps, from the entry of two 1's, which are also input with two one-finger taps. To resolve this ambiguity we could use a fixed-length, base-4 code to represent the 10 digits. This code would be 00, 01, 02, 03, 10, 11, 12, 13, 20, and 21 for digits 0 to 9, respectively. There is no ambiguity, but the code is less efficient and could still be difficult to learn.

To reduce the number of gestures per digit, we use prefix-free codes that allow for a varying number of symbols per digit with no ambiguity. The prefix-free property means that no symbol sequence for one digit is a prefix of another [12]. In the original base-4 code, 1 is a prefix of 11, which was ambiguous and led us to define the fixed-length base-4 code. In a prefix-free code, such ambiguity cannot happen and the number of symbols per digit is lower than in a fixed-length code. If all the digits are equally likely, the average number of symbols per digit is the sum of the lengths of the codes for all digits divided by 10.

As such, we developed a learnable, prefix-free code called DigiTaps$^{2.1}$ (first introduced in [22]). The digits can be derived by adding the symbols 0, 1, 2, and 3, entered by gestures, as shown in Table 1. For example, 0 is represented by a one-finger swipe, 1 by a one-finger tap, and 2 by a two-finger tap. The digit 3 is represented by a three-finger tap followed by a one-finger swipe, or 3 + 0. Similarly, 4 is represented by a three-finger tap followed by a one-finger tap (3 + 1). We represent 6 with two three-finger taps and a one-finger swipe (3 + 3 + 0). The digits 3 and 6 need a final one-finger swipe to ensure the code is prefix-free. The digit 9, however, is represented by three three-finger taps (3 + 3 + 3), since three three-finger taps are not a prefix to another input.

DigiTaps$^{2.1}$ uses 2.1 symbols on average per digit, which is close to the two symbols per digit of the fixed-length base-4 code, without the complexity of base-4 notation. An optimal prefix-free code, however, uses 1.8 symbols per digit. There are 6·10! [1]= 21,772,800 distinct optimal codes, but are any as learnable as DigiTaps$^{2.1}$?

We developed a second code, DigiTaps$^{1.8}$, which has an optimal number of symbols per digit (see Table 1). In DigiTaps$^{1.8}$, the one-finger swipe represents either 0 or 10. It represents 10 when it is the first gesture in a two-gesture digit, and the digit is derived with subtraction. For example, the digit 7 is represented by a one-finger swipe followed by a three-finger tap (10 – 3). Similarly, the digits 8 and 9 are represented by a one-finger swipe followed by a two-finger tap (10 -2) and a one-finger tap (10 – 1), respectively. In all other cases, the one-finger swipe represents 0. The digit 3, for example, is represented by a three-finger tap and a swipe (3 + 0). DigiTaps$^{1.8}$ and DigiTaps$^{2.1}$ have the same codes for five of the 10 digits.

Table 1. DigiTaps Gestures.

Digit	DigiTaps$^{2.1}$	DigiTaps$^{1.8}$
0	1-finger swipe	1-finger swipe, 1-finger swipe
1	1-finger tap	1-finger tap
2	2-finger tap	2-finger tap
3	3-finger tap, 1-finger swipe	3-finger tap, 1-finger swipe
4	3-finger tap, 1-finger tap	3-finger tap, 1-finger tap
5	3-finger tap, 2-finger tap	3-finger tap, 2-finger tap
6	3-finger tap, 3-finger tap, 1-finger swipe	3-finger tap, 3-finger tap
7	3-finger tap, 3-finger tap, 1-finger tap	1-finger swipe, 3-finger tap
8	3-finger tap, 3-finger tap, 2-finger tap	1-finger swipe, 2-finger tap
9	3-finger tap, 3-finger tap, 3-finger tap	1-finger swipe, 1-finger tap

DigiTaps Feedback

DigiTaps provides haptic and optional audio feedback that "clicks" when a gesture is entered and speaks each digit. DigiTaps' haptic feedback enables users to determine whether the system detected their gesture correctly so they can correct errors inline. In formative studies, we found that (1) participants were sometimes unsure whether their touches were registered by the system, and (2) the system sometimes registered a swipe when a tap was entered and vice versa. Thus, DigiTaps gives two kinds of haptic feedback. When the user touches the screen, the device vibrates. If the touch produced a swipe, the system pulses an extra vibration. There is no extra pulse for a tap, so the user knows which gesture was registered.

EVALUATION

We evaluated DigiTaps to find out whether it was a viable method for use with minimal audio feedback. We compared DigiTaps entry (1) with and without audio feedback, and (2) with the DigiTaps$^{2.1}$ code and the DigiTaps$^{1.8}$ code.

Methods

Participants

We recruited 16 participants to complete the DigiTaps longitudinal study (six blind, 10 sighted). Blind participants had a mean age of 45 (range: 31-57), and sighted

[1] There are 6 ways to pick the two one-symbol codes from 4 symbols, and then there are 10! possible assignments of the 10 digits to the 10 resulting codes.

participants had a mean age of 28 (range: 22-34). All had experience using touchscreen devices. We recruited blind and sighted participants through mailing lists that were affiliated with blindness organizations and university communities, respectively.

Procedure
Blind and sighted participants completed the same study procedures with one exception: sighted participants held the phone under the table (as in Clawson et al.'s study [7]), while blind people held the phone in their preferred position. Participants completed six sessions that lasted about 35 minutes each. Sessions were at least two hours, but no more than four days, apart.

In each session, participants entered sets of random four-digit sequences under four conditions: with each DigiTaps code and each feedback method (haptic only or haptic with audio). In sessions 2 - 6, participants entered 15 sequences in each condition. In session 1, they only entered sequences with audio feedback for each code, since they were still learning the codes.

We counterbalanced the order of the DigiTaps codes but did not counterbalance the order of feedback methods. We were concerned that participants would confuse the two codes if they were alternating between them and no audio feedback was given.

Apparatus
We developed an instrumented prototype of DigiTaps that ran on two Galaxy Nexus phones. The phone screens were 4.65 inches long.

Design and Analysis
The experiment had three within-subject factors: *Code* (DigiTaps$^{2.1}$ and DigiTaps$^{1.8}$), *Session* (1-6), and *FeedbackMethod* (Audio or Haptic). We computed the characters per second (CPS) and uncorrected error rate to assess speed and accuracy, respectively, following the formulas and algorithms described by Wobbrock and Myers [29,30]. The uncorrected error rate measures the frequency of errors that were not corrected by the user and appear in the final transcribed strings. Another accuracy measure, the corrected error rate, measures the frequency of errors that the user corrected. It is subsumed by the CPS, however, so we exclude it from our report.

We assessed the normality of our data through graphical means (plotting histograms and boxplots). CPS was normally distributed so we modeled it with a linear, mixed-effects model using *Participant* as a random effect. The uncorrected error rate was not normally distributed, which is usually the case with error rates. We therefore compared sample means of uncorrected error rates with Wilcoxon Signed Rank tests. We use significance levels of $\alpha = 0.05$.

Results

Entry Rate
We found that DigiTaps entry with no audio feedback was faster than with audio feedback, and that the DigiTaps$^{1.8}$ code was faster than the DigiTaps$^{2.1}$ code. This resulted in a significant effect of *Code* ($F_{(1,15)} = 6.90$, $p = 0.02$) and *FeedbackMethod* ($F_{(1,154)} = 27.28$, $p < 0.01$) on CPS. Participants significantly improved their entry rate over time, yielding a significant effect of *Session* ($F_{(1,156)} = 27.28$, $p < 0.01$) on CPS. Their improvement was about the same with both codes and feedback methods, resulting in no significant interaction effects. Table 2 shows the mean entry rates for each condition and Figure 2 shows the entry rates over all sessions of the study.

Table 2. Mean CPS rates for each DigiTaps feedback method and code.

	DigiTaps$^{1.8}$	DigiTaps$^{2.1}$
Haptic feedback	0.89 (SD = 0.31)	0.85 (SD = 0.32)
Audio feedback	0.82 (SD = 0.36)	0.78 (SD = 0.34)

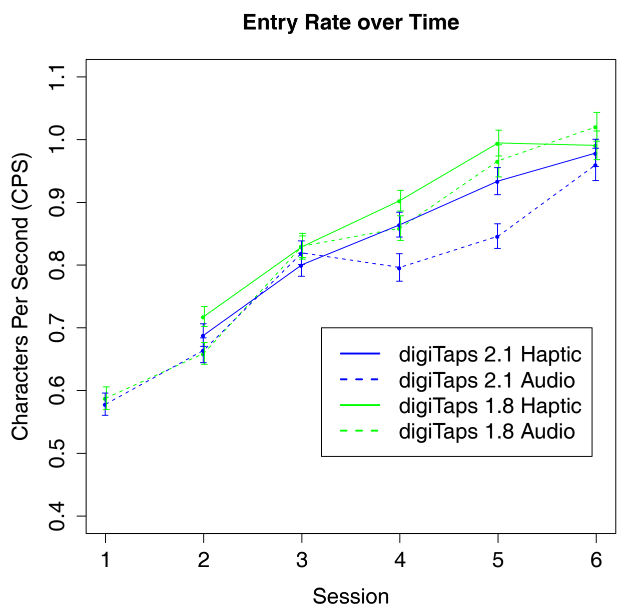

Figure 2. Entry rates for the six sessions of the study. The error bars show the standard error of the means. Higher numbers are better.

Accuracy
The uncorrected error rate was higher for haptic feedback than for audio feedback. This resulted in a significant effect of *FeedbackMethod* ($W = 5$, $p < 0.01$) on Uncorrected Error Rate. There was no significant difference between the uncorrected error rates for DigiTaps$^{2.1}$ and DigiTaps$^{1.8}$. Participants made fewer errors as the study progressed, and we found a significant effect of *Session* ($F_{(1,156)} = 15.69$, $p < 0.01$) on the uncorrected error rate. Table 3 shows the mean

entry rates for DigiTaps feedback methods and codes and Figure 3 shows how they changed over time.

Table 2. Mean uncorrected error rates for each DigiTaps feedback method and code.

	DigiTaps$^{1.8}$	DigiTaps$^{2.1}$
Haptic feedback	5.58% (*SD* = 14.6)	5.68% (*SD* = 15.0)
Audio feedback	2.17% (*SD* = 8.96)	2.22% (*SD* = 8.7)

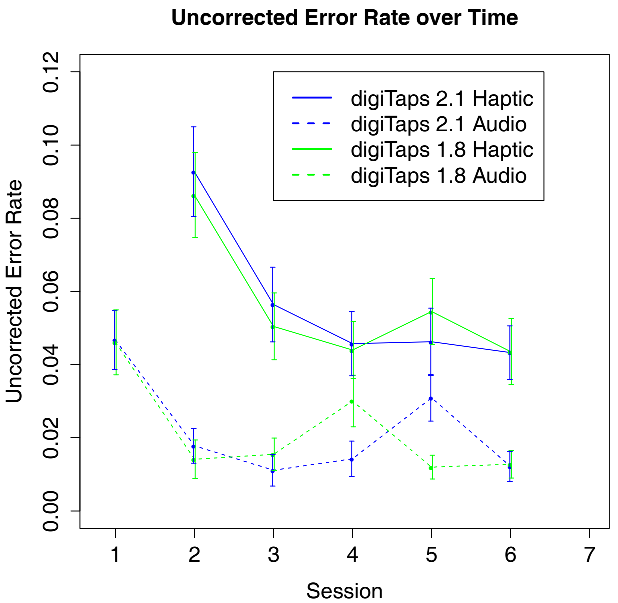

Figure 4. Uncorrected error rates for the six sessions of the study. The error bars show the standard error of the means. Lower numbers are better.

Subjective Preference

We asked participants which method they preferred at the end of the study. Twelve (71%) out of the 16 participants preferred DigiTaps$^{1.8}$, citing its speed and the lower number of taps per digit. A one-sample Pearson Chi-Square test of proportions showed that this preference was significantly different than chance, ($\chi^2_{(1,N=16)} = 4.00$, $p = 0.046$).

DISCUSSION

Overall, we believe the speed and accuracy results show DigiTaps is a promising eyes-free technique. Prior work [5] showed that blind iPhone users entered a familiar 4-digit PIN in 7.52 seconds on average with VoiceOver. With DigiTaps, blind and sighted people entered randomly generated four-digit sequences in 7.01 seconds after only the first study session. During the final session, they entered four-digit sequences in 4.1 seconds on average. Moreover, participants' rate of improvement (shown in Figure 2) suggests their entry speed will continue to increase with more practice.

Number entry with only haptic feedback was faster but also less accurate than entry with haptic and audio feedback. The former was faster probably because users did not pause after each entry to hear the spoken digit, and did not correct as many of their errors. We were pleased that by Session 6, the uncorrected error rate was still rather low, at only 4.6%. However, it is difficult to draw conclusions from the comparison of methods of feedback, because we did not counterbalance the order of the audio and haptic conditions in the study. There may have been carry-over fatigue or learning effects from the audio condition. Nonetheless, it seems likely that performance with only haptic feedback was not substantially *worse* than with audio feedback.

There was a small, albeit statistically significant, difference between entry rates between DigiTaps codes. DigiTaps$^{1.8}$ was faster than DigiTaps$^{2.1}$ with no speed-accuracy trade-off. Surprisingly, even though most participants felt DigiTaps$^{2.1}$ was easier to learn, performance with both codes was nearly equal in the first session. In later sessions, the difference in speeds between the codes was small, but most preferred DigiTaps$^{1.8}$.

We believe our results show that DigiTaps offers a new approach to eyes-free input that requires *minimal* audio feedback. Blind people would still need audio feedback to confirm the numbers they entered were correct; they would also need audio feedback for any other verbal output from their device. However, they wouldn't be as reliant on the audio feedback when entering numbers with DigiTaps. A blind person could sit in a loud café and comfortably enter a number without holding the device up to his or her ear. DigiTaps could be useful for sighted people as well. A sighted person could enter a street address while walking and glance down to ensure it was correct. Eyes-free minimal audio interaction would enable people to use their touchscreen devices more comfortably in a variety of situations.

CONCLUSION

We have presented DigiTaps, an eyes-free number entry method with minimal audio feedback. The design of DigiTaps was guided by learnability, efficiency, and complete eyes-free accessibility. We conducted a longitudinal study with 10 sighted and six blind participants, finding that entering numbers with DigiTaps was faster but less accurate when audio feedback was removed. We believe this trade-off shows that DigiTaps is a promising method for entering numbers in situations where it is difficult to hear a device's audio feedback. DigiTaps, along with other interaction techniques that require minimal audio feedback, will enable blind people to use mobile devices in a wider range of contexts.

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