

Passive Haptic Learning of Braille Typing

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ABSTRACT

Passive Haptic Learning (PHL) is the acquisition of sensorimotor skills without active attention to learning. One method is to "teach" motor skills using vibration cues delivered by a wearable, tactile interface while the user is focusing on another, primary task. We have created a system for Passive Haptic Learning of typing skills. In a study containing 16 participants, users demonstrated significantly reduced error typing a phrase in Braille after receiving passive instruction versus control (32.85% average decline in error vs. 2.73% increase in error). PHL users were also able to *recognize and read* more Braille letters from the phrase (72.5% vs. 22.4%). In a second study, containing 8 participants thus far, we passively teach the full Braille alphabet over four sessions. Typing error reductions in participants receiving PHL were more rapid and consistent, with 75% of PHL vs. 0% of control users reaching zero typing error. By the end of the study, PHL participants were also able to *recognize and read* 93.3% of all Braille alphabet letters. These results suggest that Passive Haptic instruction facilitated by wearable computers may be a feasible method of teaching Braille typing and reading.

Author Keywords

Haptic; Tactile; Wearable; Interfaces; Typing; Text Entry; Passive Learning; PHL; Learning; Braille; Blind

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: Miscellaneous.

INTRODUCTION

Passive Haptic Learning (PHL) is the acquisition of motor skills through vibration stimuli, without devoting active attention to the stimulus [6]. Users wear a tactile interface for a period of Passive Learning and, even while they focus on a mentally taxing task such as a standardized test, learning of "muscle memory" still occurs [7]. When the learning period is complete, users remove the wearable, tactile interface and are able to perform a manual skill such as playing a piano melody [6].

Wearable computers, such as gloves, administer the tactile stimuli that teach users during PHL. Gloves for PHL have a programmed, embedded, tactile interface that uses vibration motors sewn into each finger to deliver sequences of short vibrations across the hands. These sequences encode meaning, such as the pattern of finger-presses used to play a piano melody [6, 7, 8] or the keyboard keys that type a phrase [11]. The previous work on Passive Haptic Learning focused on teaching these rote order tasks for piano [7]; while this project's initial work demonstrated PHL of typing skills on a 10-key, non-chorded keyboard in three users [11]. Here, we present a system to facilitate Passive Haptic Learning of Braille typing skills and two studies evaluating its effectiveness.

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BACKGROUND AND MOTIVATION

Previous Work

Haptic guidance can help users learn manual skills [3, 5]. This learning can still occur if the user is distracted by performing another task. Previous work has established that PHL effectively aids learning of rote patterns of muscle memory for the fingers of *one* hand. The Mobile Music Touch (MMT) project demonstrated passive learning of a pattern of keys that play a piano melody. In this research, users wore a PHL glove (wearable, tactile interface) while doing other tasks, such as taking a test or doing homework. The glove system played the song to be learned and stimulated the appropriate finger for each note. Users could ignore the vibrations, perform distracting tasks, and learning still occurs. Studies showed that participants were able to learn 45 notes of simple melodies, such as Ode to Joy, in 30 minutes using this method [6].

In a feasibility study reported as a Work In Progress at CHI 2014, three participants passively learned how to type a phrase on a randomized, 10-key keyboard with a non-chorded, 1-finger-to-1-key mapping. The keyboard contained letters 'A'-'H', space, and enter. Users in this study wore a pair of gloves with embedded vibration motors and focused on playing a memory card game for 30 minutes while repeatedly hearing the phrase spoken and feeling the corresponding finger pattern (to type the phrase) stimulated. At the end of this PHL session, users were able to type the phrase with less than 20% error. They were also able to type the components of the phrase (words and letters) without error, and understood the mapping of the keyboard enough to type a new phrase with <20% error [11].

Here, as compared to previous work we:

- Demonstrate that Braille typing skills can be "taught" without active attention of the learner
- Articulate a method of teaching chorded input using a sequential tapping pattern (previous efforts at teaching chords failed)
- Establish a method for teaching the entire Braille alphabet in four hours
- Demonstrate that Braille letter identification, both visually and tactilely, can be a side effect of learning to type Braille
- Introduce a distraction task with more sensitive performance metrics

Motivation

39 million people in the world are blind. Learning to type the Braille system is time consuming and a major component of the rehabilitation and independence training for individuals who are blind or visually impaired. Braille is especially difficult to learn for those who lose their sight later in life, such as the aging population, wounded veterans, and the increasing number of diabetics. What's more, Braille instruction is neglected in schools; with only 10 percent of those who are Blind able to learn Braille [2].

The National Federation of the Blind calls illiteracy among the Blind a ‘crisis’ [2]. Because of a lack in certified teachers and bureaucratic barriers to providing education, blind and low vision students are not being taught Braille. For these individuals though Braille equates to reading and writing, and without this education, they are illiterate [1, 10]. The problem doesn’t end here; Braille literacy directly correlates with academic success and employment (even in contrast with those proficient with screen-readers) [1], leaving 74% of blind individuals unemployed. Mainstreaming blind students in the public school system, where significantly less time is available for learning Braille, is another significant cause for this crisis; the influx of speech in technology is also causing neglect in Braille instruction. Listening alone is not enough, however, as research shows that Braille provides a critical advantage for students in learning math, grammar, language, spelling, and science [10]. Blind individuals, adults and students alike, even try to attend Rehabilitation Centers to gain these necessary skills for independent living. However, access to these facilities is difficult and requires a commitment to seven or more months of inpatient learning. There are only 12 such facilities in the United States, and for many, access to instruction here is also impossible because of financial or geographic constraints. Current technology for Braille instruction is limited to refreshable Braille displays and electronic Brailers. Methods used to teach Braille today involve tactile flash cards, block models of the Braille cell and hand guidance of the individual's fingers. Users first learn to read, then type letters [4].

The lightweight and wearable system that we are developing aims to teach Braille typing to those without access to instruction. Our work aims to reduce learning time and difficulty by allowing patients to passively learn while doing other tasks such as cane training, orientation and mobility or even tasks in their daily life or at home. With knowledge of the direct mapping between the keys of the Braille keyboard and the dots that comprise Braille, our system for PHL of typing skills may even help individuals to learn to read Braille as well. This research aims not only to explore the subject of Passive Haptic Learning, but to also create this system to aid Braille instruction.

STUDY #1 - TWO PHRASE EXPERIMENT

In our first experiment, containing 16 participants, we examine whether Braille typing skills can indeed be learned passively. To evaluate this, we measure user performance on typing tests surrounding learning periods. During each study session, the user is given a pre-test before any learning, then performs a distraction task with or without simultaneous Passive Haptic Learning. The session concludes with a typing post test and Braille reading quizzes. The distraction task is scored so we can examine PHL's effect on user performance. We present Braille reading quizzes to examine whether there is a transfer of knowledge between Braille typing and reading skills. Each user participates in two sessions: one with PHL and one with none (control). All users learn one of two phrases during their first session, and learn the remaining phrase during their next session. The experiment is counterbalanced for phrase and condition. Participants are all native English speakers who did not know Braille.

SYSTEM

This system includes a pair of gloves with one vibration motor in each finger and a programmed microcontroller to drive the glove interface. The microcontroller coordinates vibration timings and sequences to correspond with audio prompts for two phrases. For convenience, we created a Braille keyboard from two BAT keyboards. The system is shown in Figure 1.

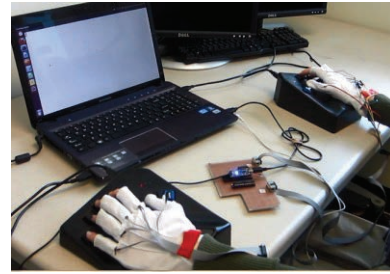


Figure 1. System in use during a typing test.

Gloves

The wearable, tactile interface used to deliver vibration stimuli is in the form of a pair of gloves. The gloves are fingerless for optimal fit on different size hands, enabling the motors to rest flush near the base knuckle of each finger. Each motor is secured to the stretchy glove layer using adhesive and is located on the back of the hand (dorsal, non-palm-side) inside the glove. These gloves utilize Eccentric Rotating Mass (ERM) vibration motors (Precision Microdrives model #308-100) and are driven High or left floating through a Darlington Array chip attached to an Arduino Nano with buffered circuitry.

Audio and Vibration Sequences

Braille is a chorded language, meaning that multiple keys are required to type one alphabet character. Rather than deliver stimuli simultaneously to all fingers used in typing a given chord – human perceptive ability of these simultaneous stimuli is yet unknown – we ‘stagger’ each chord’s vibrations by activating the motors sequentially instead. We use audio and timing cues to indicate the completion of a chord (letter) to users.

There were two circumstances in which vibration and audio are used together for this study: once during each pre-test and during Passive Haptic Learning. During both these times, users are presented with audio of each word in the session’s phrase followed by the audio spelling of that word. After each letter is spoken, the motors on the fingers required to type that chorded letter are each vibrated in a sequence. When that chord is finished, the system pauses for 100ms before playing the audio for the next letter. This audio-haptic stimulus is repeated for the entire distraction task period for PHL, with 10 seconds rest in between each repetition. Motors were activated for 300 to 750 ms, and phrase vibration sequence timings were chosen to enable clear discrimination and recognition of vibrations and separate chorded letters. This results in approximately 60 repetitions of the phrase during the distraction task period.

Keyboard

The Braille keyboard used in this study consists of two Infogrip BATs. BAT keyboard inputs are translated into Braille keyboard entries. Key presses generate ASCII characters that are translated to the appropriate Braille value from a hash-map. Both ‘staggered’ entry (pressing one key down at a time and then releasing all of them) and simultaneous entry (pressing all the required keys down at the same time) are supported. This technique produces a chorded input system that follows the Perkins Brailier standard as digital Braille keyboards do, such as Freedom Scientific’s PAC Mate.

Typing Software

Typing test sessions in our studies are administered by specialized typing software. The software prompts the user via audio and shows a blank screen. Upon each successful entry of a Braille letter or space, the screen displays an asterisk (to prevent learning

during testing, and provide feedback on correct entry technique) [11]. This software logs user input and performance, and calculates statistics like uncorrected error rate (UER) and words per minute (WPM) using formulae detailed by MacKenzie & Tanaka-Ishii [9].

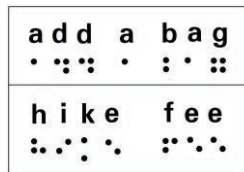


Figure 2. Phrases used in our first study.

Phrases

The phrases (Figure 2) used in this study are ‘add a bag’ (AAB) and ‘hike fee’ (HF), and were chosen for easy identification via verbal audio clips, in consideration of findings in previous related work [11, 12]. These phrases do not include homophones, difficult or little-known spellings, and have coherent meanings for easy understanding and memory. They were also chosen to be of comparable length (15-18 vibrations), an established length from previous work in Passive Haptic Learning of piano and typing [8, 11]. Finally, these phrases consist of Braille letters requiring no more than three keys each to type and have comparable complexity (repeated letters, 4 or 5 unique letters, containing words of 3-4 characters).

STUDY

Pre-test

Initial performance of users is determined through a typing pre-test. Study administrators use a verbal set of instructions and gestures to introduce participants to the keyboard and the nature of typing chords. This procedure allows users, who all come from an uninformed position, to understand the nature of typing on the chorded keyboard and to comprehend the meaning of the audio and vibrations. At the start of the pre-test, participants hear the current phrase’s audio and feel the corresponding vibration sequence once before being prompted to try typing the phrase. Users are given one trial at typing the phrase during the pre-test. During this first vibration-guided pre-test, they are asked to pay attention to understanding the meaning conveyed by the vibrations, and to use the pre-test to understand how to correctly type chords on the keyboard. Results from this pre-test are used as a baseline for users’ typing performance.

Distraction Task

After the pre-test, subjects in both PHL and control conditions participate in a distraction task. The distraction task lets the subjects focus on tasks other than PHL and measures their ability to perform while receiving the stimulus. Both groups are given 30 minutes of distraction task with the gloves on and ear buds in. In our studies, the distraction task used is an online game. Users are told to focus only on the game and give any audio and vibrations no attention. During the task, both groups are also asked to score as high as possible. At the end of each distraction task period, their scores are logged.

For this study, the distraction game was chosen to:

- be difficult/cognitively demanding/mentally taxing
- contain no reading/words
- emit no sounds/mutable
- log a score

The game Fritz! [13] was selected as the distraction task and was administered to both groups. Before the game, all subjects are

provided with instruction on how to play. The goal of Fritz is to clear levels of blocks by aligning those of similar patterns through moving adjacent blocks. If users are experiencing a PHL study session, they receive haptic and audio stimulation while they play the game. Control groups are provided with neither PHL audio nor vibration. *For the purpose of the study, PHL groups are specifically told not to pay any attention to the vibrations or audio and to focus entirely on the game.*

Post Test

After the distraction task, users are given a typing (post) test. During this test, participants are first prompted to type the entire phrase they just learned (and/or attempted during the pre-test). They are given three trials to type the full phrase, before being prompted (for three trials) to type each word in the phrase, and each letter in the phrase (presented in random order). Participants feel no vibrations during the test.

Braille Reading Quizzes

The goal of this research is to examine the potential of Passive Haptic Learning for the application of learning **typing skills** on the Braille Keyboard. There is a linear mapping between the Braille Keyboard and the dots of the Braille cell, so we chose to add Braille **reading** quizzes in addition to Braille typing tests – on the off-chance that participants could use the typing skills they passively learned to understand and read Braille as well. The quizzes were designed to determine if this transfer occurred or not. Recruiting from a pool of sighted individuals that do not know Braille; we understood that tactile perception may be difficult for these untrained individuals. For this reason, we included reading quizzes that use visual representations of Braille, in addition to ‘tactile quizzes’ using embossed Braille representations.

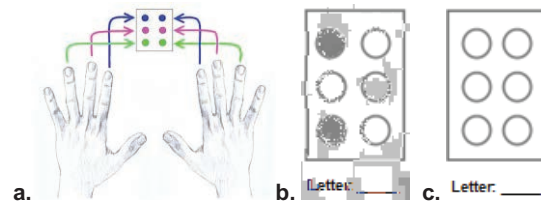


Figure 3. (a.) Mapping diagram on quizzes. (b.) Visual quiz question example. (c.) Tactile quiz answer sheet example.

We administer two quizzes at the end of each session. The visual quiz is presented before the tactile quiz because we assume it to be the simpler of the two; while the tactile quiz combines Braille typing-to-reading ‘translation’ with tactile perception.

At the beginning of both quizzes, instructions are provided that describe how the finger mapping of the keyboard aligned with the dots of the six-dot Braille cell. Study administrators also demonstrate this mapping using our hands in combination with a verbal set of instructions to ensure participants correctly understand the relationship. The picture used on the quizzes to convey the mapping can be seen in Figure 3a.

Visual Quiz

The visual quiz is comprised of images of Braille cells with dots filled-in or left empty to illustrate what would be embossed on a printed Braille document. We created one question for each letter from the phrase they were assigned. “add a bag” session users are quizzed on the phrase’s letters in the consistently randomized order: d, g, b, a. For the “hike fee” session they are quizzed in the order: f, i, e, k, h. Each question shows a Braille cell image (Figure 3b) and asks users to write-in the letter it represents.

Tactile Quiz

The Tactile Quiz was designed to understand whether the student can perceive the Braille cells with their fingers, and whether they can identify the letter from what they perceived. For this quiz, the subject places their dominant hand into a box, open only on one side, which contains a card embossed with the current letter from the quiz. This setup allows the subject to slide their hand in and access the Braille with their fingers without *glimpsing* the Braille on the card. Participants were given the same letters that appeared in their visual quiz but in a different consistently randomized order (b, g, a, d and h, e, f, i, k). After the student feels the Braille cell using their fingers, they bubble-in a blank Braille cell on the quiz - three rows of two small empty circles - to indicate what they perceived (Figure 3c). Subjects also fill-in a blank with their identification of the embossed letter.

RESULTS - TWO PHRASE STUDY

With the aid of PHL, participants significantly reduced typing error rates on the Braille keyboard, often reaching 100% accuracy. Users also *learned to read* nearly 75% of the Braille letters presented. These findings suggest that users learned some Braille/chorded text entry via Passive Haptic Learning.

Typing

Our team's typing software calculates uncorrected error rate (UER) and words per minute (WPM) [9] which we use for analysis of the participants' performance. As this study was within-subjects, paired t-tests are used to compare the effect of receiving PHL versus not having PHL. Because our *a priori* hypothesis is that PHL will improve performance on phrase and letter typing accuracy and visual and tactile recognition of letters, no familywise multi-hypothesis correction was necessary. Threshold of significance was set to $\alpha = 0.05$.

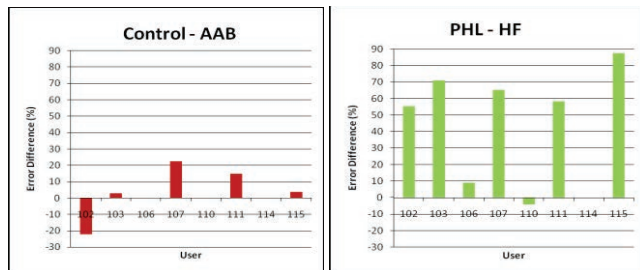


Figure 4. Typing accuracy improvements for participants who typed 'add a bag' in their control session and 'hike fee' for their PHL session.

Comparing the typing error rate in the pre-test trial with the average error rate of the three phrase-typing trials on the post-test, the UER (uncorrected error rate) difference was calculated and graphed for each user's sessions. For both phrases, as seen in Figures 4 and 5, users reduced their typing error (increased accuracy) significantly after passive learning sessions (31.55% and 42.78% on average).

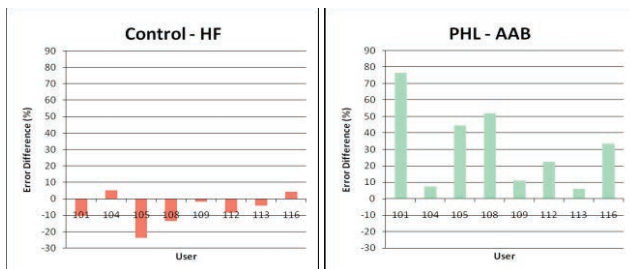


Figure 5. Typing accuracy improvements for participants who typed 'hike fee' in their control session and 'add a bag' for their PHL session.

This result was not true for control sessions, where minimal to no improvement (2.68%) was the norm for 'add a bag' and increased errors (up 7.14%) was the norm for 'hike fee'. This data is represented in the average improvements in accuracy for each phrase (Figure 6). A paired t-test suggests a statistical difference in the conditions: participants given PHL have a larger AER difference (39.14) between pre-test baseline performance and post-test performance ($M=37.16$, $SE=30.22$) than people not given PHL ($M=-1.97$, $SE=11.98$; BCa 95% CI[22.0, 56.27], $t(15) = 4.87$, $p<0.00001$). When a participant was asked to type each single letter from the phrase, the number of correctly typed letters was significantly higher for PHL sessions than for control (Fig. 7).

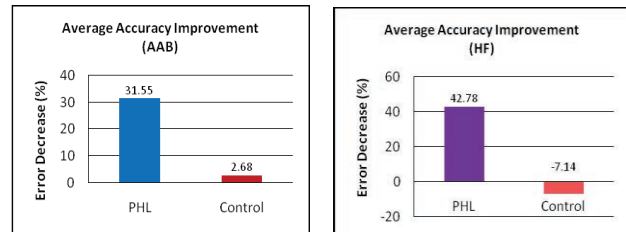


Figure 6. Average typing accuracy differences.

T-tests illustrate that there is a statistical difference (2.31) in the number of correct letters typed between the conditions when participants are given PHL ($M=3.25$, $SE=1.69$) than people not given PHL ($M=.94$, $SE=1.12$; BCa 95% CI[1.33, 2.31]; $t(15) = 5$, $p<.00001$).

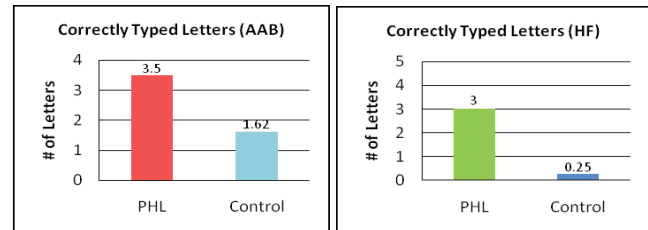
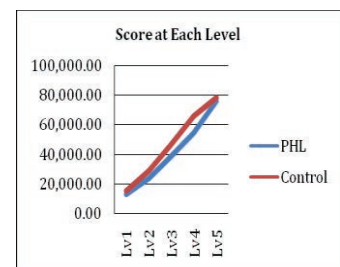


Figure 7. Letters typed correctly between conditions for both sessions.

Distraction Task

We wish to characterize the base performance for our participants on the distracter task, the Fritz! game. A player not in the PHL study conducted three trials of his game play. Each trial consisted of 10 minutes of a focused session and a distracted session. During the focused session, the player played the game only. For the distracted session, the player was instructed to play the game while attending a television program as well. The player showed reduced scores during distracted game sessions by an average of 19.36%.

All 16 subjects played the game for each PHL and control sessions and cleared up to level 5 during the 30 minutes. Results for performance differences were noisy due to the nature of the game, but average score differences between PHL and control were found to be within 10% as seen in the graph at the right. These results help to demonstrate and reconfirm the sensitivity of our chosen distraction task at monitoring user attention and mental resource sharing.



Reading Braille

Average score (letters identified correctly) is used to compare the tactile and visual quiz performance of participants that were given PHL and those that were not (control group). For sessions assigned either phrase, participants that were given PHL performed significantly better on reading (identifying) Braille letters. All users had near perfect tactile perception of the Braille cells; thus, PHL had little to no effect on the perception of letters on the Braille cards.

'add a bag' Phrase Performance

As seen in Figure 8 left, performance on the Braille *reading* quizzes was better in PHL than in control. Users were able to **read** 91.7% of the phrase's letters in Braille after receiving Passive Haptic Learning. Perception (of embossed Braille dots with the fingers) was nearly even between the groups, and on average, untrained users' tactile perception of the dot configurations was excellent (near 4 of 4 letters). Identification accuracy (# of correctly recognized letters) of the embossed (tactile) Braille was close to the same as identification accuracy during the visual test. If a participant was able to correctly perceive a Braille letter, their accuracy at correctly identifying that letter typically mirrored their ability on the visual quiz.

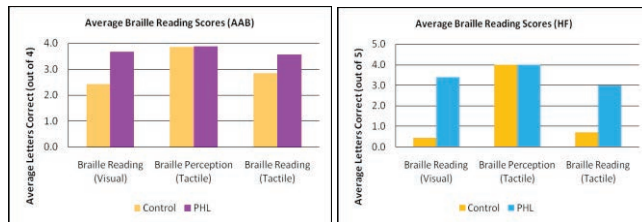


Figure 8. Reading scores between conditions for both sessions. Left 'visual' bars are from visual quiz results, while right 'tactile' bars present results from the tactile quiz.

'hike fee' Phrase Performance

Findings from the 'add a bag' quizzes remained consistent in 'hike fee' sessions as well, with the PHL group far outpacing the control group. As also seen in typing scores, group differences were more evident in HF performance. The average number of accurately identified letters differed between the control group and the PHL group by three letters out of five. PHL participants again showed no difference in perception of Braille dots using the fingers (on the tactile quiz) from those that didn't receive passive learning; while identification on the tactile quiz for the PHL group was on average 2.3 letters better. Passive Haptic Learning participants did significantly better in reading Braille than the control group. This result is shown in Figure 8 right.

DISCUSSION – TWO PHRASE STUDY

Results of this initial study indicate that Passive Haptic Learning of chorded text entry is indeed possible. Typing test results show that users can learn to type Braille **passively** through vibration and audio stimuli alone. Study administrators observed users typing not only 'staggered' input for each letter, but also simultaneous chorded input. This observation supports the idea that, given our current system structure, users were able to grasp the nature of chorded typing as well as understand the meaning of the audio and vibration sequences (that users received during the vibration-guided pre-tests and PHL period).

A larger performance gap is found in HF sessions. We believe this effect is indicative of the phrase's higher difficulty. Though we designed phrases to be as well-matched as possible, 'hike fee' has five unique letters and more vibrations which undoubtedly results in some increased difficulty. This difficulty lets users learn less of the phrase

during the pre-test, the source of any knowledge in the control group; while PHL users could successfully passively learn the difficult phrase.

Distraction task performance helped confirm that users paid little attention to the vibration and audio stimulation during PHL. Score differences were minimal, though they may indicate some mental resource sharing by this spatially-based game and our passive stimuli. Experimentation using this game indicates its sensitivity in scoring and that it fits well with our parameters. In our experience with PHL of piano melodies, the audio is a larger distraction than the vibration [7]. Perhaps an improvement to study design would be to have the control condition also receive the same audio stimuli as the passive condition. In practice, however, our goal is to create a system by which users can acquire Braille typing skills with little perceived effort. If PHL for Braille is a mild distraction while performing another task, our goal is still reached.

Remarkably, we found that users could transfer knowledge learned in typing on the Braille keyboard to *reading* Braille. This result – acquisition of **Braille reading skills** through (passive learning of) **Braille typing** – has intriguing implications. During the entire study, users were in the 'asterisks' condition of uninformative feedback for all typing tests [11], meaning that users never see what they type on screen and had no indicators whatsoever of their correctness throughout the entire study. The only learning participants received was guided by the haptic interface – not an inappropriate mechanism considering the target audience (users who are blind). We intend to make use of this finding, and our findings here on successful Passive Haptic Learning of Braille typing, to affect this audience. Application of this technology can be used to help improve Braille literacy.

Several components of our findings on Braille reading are of note. As could be expected, perception using the fingers was the same for both PHL and control groups. Interestingly though, our sighted, untrained pool of users were able to correctly perceive embossed Braille using their fingertips. Within each group (PHL or control), users identified nearly the same Braille letters during both the visual and tactile quizzes, a logical finding – if a user knows a letter visually, then they know that letter tactilely as well. A prominent finding regarding identification (reading) is the gap between those with Passive Learning and those given only the pre-test introduction. This result coincides with congruent results of user typing performance, indicating more strongly that users passively learned. Encouraged by the results of this feasibility study, we expand this work to examine teaching typing of the entire Braille alphabet passively.

STUDY #2 – FULL ALPHABET STUDY

Above, we focused on the internal validity of our study to determine if Passive Haptic Learning of Braille typing skills is possible. Here, we begin an investigation of a larger goal: making and studying a system that facilitates Passive Learning of typing the full alphabet in Braille.

This study is our first investigation into making and testing a real-world passive Braille instruction system. For the Full Alphabet Study, we increased the number of sessions and decreased the amount of time spent in PHL. We teach an 8-word pangram passively, one word at a time. The study is four sessions in length, each session composed of two compressed "mini-sessions" containing a typing pre-test, distraction task, typing test, and reading quizzes. Each of these mini-sessions are structured in the same way as sessions were in the Two Phrase Study, but distraction task periods last only 20 minutes. We chose to reduce the time for Passive Haptic Learning (which occurs during the distraction period), because oftentimes in the Two Phrase Study users encountered a ceiling effect (0% error in PHL) for the 4-letter (9 character) phrase over 30 minutes. This study is also a trial at exploring the necessary time for PHL and at reducing the overall time to learn Braille.

Using this structure, we conducted a randomized, controlled, between-subjects study of the full alphabet system on eight participants thus far (all sighted, native English speakers who did not know Braille). Each user was designated as either PHL or control and received only that condition throughout the study. Every mini-session corresponded to a word in the pangram #1, and users learned 2 words per visit (2 mini-sessions per session). All users learned the pangram's words in order (the repeated 'the' was omitted between 'over' and 'lazy').

Pangram #1 for PHL

With the intent of teaching how to type the full alphabet, we utilize a pangram as a set of words to passively train the user. A pangram contains all 26 letters of the alphabet at least once, and forms a sentence in English. The sentence we chose as the main pangram, to be used in Passive Haptic Learning, was "the quick brown fox jumps over the lazy dog." This pangram was chosen over others for four primary reasons. The sentence is coherent and familiar to many English speakers, which enables users to remember and understand the phrase seamlessly. This pangram was chosen also because it uses non-ambiguous words with few homophones, an important consideration when using audio prompts [11, 12]. Words in the pangram are also of nearly equal lengths, with 3-5 letters and 10-17 vibrations each, remaining consistent with previously determined optimal lengths for PHL phrases [8, 11]. Finally, this sentence contains just eight unique words and repeats only four letters.

SYSTEM

We updated the system to provide audio prompts for the necessary content to be used in the typing pre-tests and tests (which maintained similar structure to those of the Two Phrase Study). Prompts for the PHL pangram #1 consisted of only audio of the phrase or word. Audio prompts for the untaught #2 pangram (introduced in the post-test section) each consisted of the word, followed by its spelling. This procedure was done for clarity of understanding on the part of the user, as this pangram is both uncommon and unfamiliar, and contains words with potentially unknown spellings. This method also emphasizes the composition of the word, allowing the participant to type the letters that they have already learned even though they have not learned the full/self-contained word.

The typing software was also updated to display informative feedback [11] (letters typed) to the user. We made this change – from displaying only asterisks to displaying letters typed – because of our goal for the Full Alphabet Study: examining whether PHL can be used to teach typing of the entire Braille alphabet (the Two Phrase Study sought to establish the internal validity of Passive Haptic Learning of chorded typing skills). Here, we aim for the feedback to help reinforce learning and encourage confidence.

The gloves with embedded tactile interface of ERM vibration motors remained the same for this study, as did the Braille keyboard. Audio and vibration sequences maintained the same structure, with each word being spoken, followed by its spelling coordinated with each letter's keys vibrated in sequence.

STUDY

Pre-test

During the first pre-test only, users receive the full pangram #1 with coordinated vibration once and do not receive vibration stimuli again in the study except during PHL. Similarly to the Two Phrase Study, participants then have a chance to type the full pangram. This initial vibration-guided trial (only in the very beginning of the study, in mini-session "the"), is followed by a standard pre-test present in all mini-sessions. This pre-test consists of one trial each at typing the entire pangram #1 and then each word that it contains (presented in a

random order). Pre-tests form the baseline in user performance before each PHL (or control) period. Introductions to chords and the initial vibration sequence are identical to procedures from the previous study.

Distraction Task

In this between-subjects study, users who were designated as PHL received audio and vibration stimuli during the distraction task, while those in the control group received only the audio of the current word repeated on a loop. The same online game is used in this study as in the Two Phrase Study. During each mini-session, users are told not to pay any attention to the vibrations or audio and to focus all their attention on doing their best at the game.

Post Test

Following each distraction task period, users are given a typing (post) test. Participants feel no vibration during the test and hear audio prompts provided by the typing software. The test consists of three trials at typing the mini-session's word, followed by three trials typing each of the letters in that word (in a randomized order), and three trials at typing the full pangram #1. The test then prompts users to type each word in the 'untaught' #2 pangram, presented in random, giving them three trials for each of these words as well, before concluding with one trial typing the full untaught pangram.

The #2 'untaught' pangram was selected to be "when zombies arrive quickly fax judge pat" based upon the same factors for selection of the PHL pangram – contains coherent meaning, similar word lengths (10-18 key-presses each), and contains few repeated letters.

Braille Reading Quizzes and Full Tests

The structure and administration of the (visual) quiz and tactile quiz was the same as was utilized in the Two Phrase experiment. Quizzes were created for (the letters in) each of the 8 words in the PHL #1 pangram and were presented at the end of that word's mini-session.

Following the completion of the final Quizzes (at the end of the fourth visit, mini-session 'dog'), the full test and full quizzes were given. The full typing test consisted of three trials at typing every letter of the alphabet. The full quizzes were a visual and a tactile reading quiz containing a randomized list of all the letters of the alphabet.

RESULTS - FULL-ALPHABET STUDY

Users receiving PHL outperformed those that did not. This finding was true for the full pangrams/alphabet as well as for individual words. Data indicates that a system for PHL instruction of Braille can rapidly and successfully help individuals learn reading and typing *passively*.

Typing Phrases

Participants receiving PHL throughout their learning time showed greater improvements in performance, often reached perfect performance, and did so in less time than those without passive learning.

As illustrated in Figure 9, participants experiencing PHL were able to reduce their errors in typing the main pangram #1 phrase more rapidly and consistently. A single-factor ANOVA was also performed on the groups' pangram typing error rates over the study's 16 tests, and it found a statistical difference between the conditions ($F=10.05$, $p<0.0001$). Because of the informative feedback [11] used during testing periods, control users learned some letters through Active Practice trial-and-error; however, their learning was highly variable and more gradual. No users in the control condition achieved 0% error; while 3/4 users receiving PHL reached perfect performance on average before the final session.

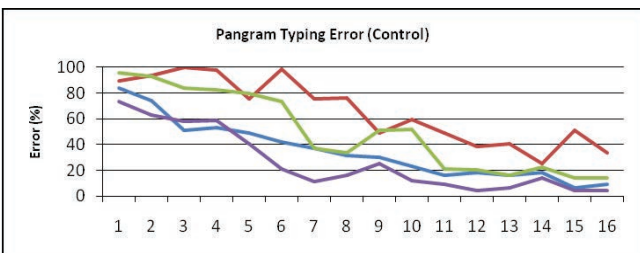
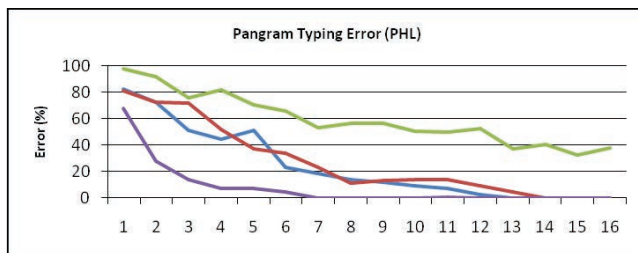


Figure 9. Pangram #1 ('the quick brown...') phrase error rates for each user through all eight mini-sessions (pre-test and post test each).

These results suggest that PHL can be used to reduce learning time and difficulty for people learning Braille typing. Users not receiving PHL had significantly more variation in their number of typing errors. The near monotonic decrease in error for participants given PHL suggests that, as in previous work [7], passive learning may be aiding in passive rehearsal as well. Similar effects can be seen in user performance of the second 'untaught' #2 pangram during the tests, as is illustrated in Figure 10. Single-factor ANOVA results for this pangram's (#2) typing error rates over the 8 tests again found statistical difference ($F=7.138, p<0.0001$).

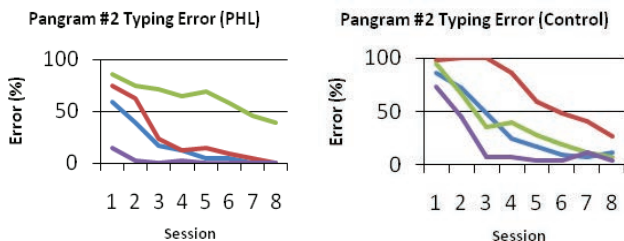


Figure 10. Pangram #2 ('when zombies...') phrase error rates through all eight mini-sessions (phrase is only in the post test).

Typing Words

As in the Two Phrase study, users receiving PHL illustrated UER differences between pre-tests and post-tests for each word. These improvements in PHL users' performance can be seen in Figure 11, which shows differences in error rates before and after passive instruction (or lack thereof) of that word. Words at the beginning of the pangram are highlighted in the image because this performance difference is most visually noticeable in initial sessions, before PHL users achieve 0% error on that word (while there is still room for improvement).

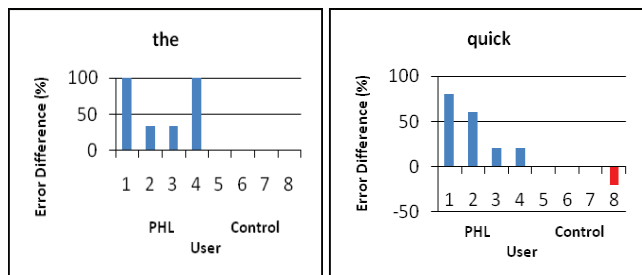


Figure 11. Pre and post test error rate differences for 'the' and 'quick' in the mini-session devoted to learning that word. PHL participants are labeled here as 1-4, control 5-8.

Figure 12 gives another view on the difference in word typing performance between PHL and control groups. On later words in the phrase, PHL participants have now achieved 0% error and control participants continue to stagnate around 30-60%.

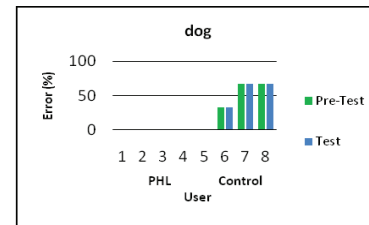


Figure 12. Pre- and post test error rates for 'dog' in the mini-session devoted to learning that word. PHL participants are labeled here as 1-4, control 5-8.

Distraction Task

From distraction task scores analysis, data shows that the control subjects showed better average performance than PHL by 3.03%. The more equitable performance between groups compared to our first study may be due to the addition of audio stimuli during the distraction task in the control group. This result suggests that users undergoing Passive Haptic Learning heeded instructions and did not pay attention to the vibration stimuli.

Reading Braille

As seen in Figure 13a, PHL participants also out-read users in the control group to achieve high levels of correct Braille reading in all words' tests. Those who received Passive Haptic Learning correctly read within one letter of possible on average for each word's quizzes; while control users identified fewer letters. Identification accuracy on tactile quizzes followed that of visual quizzes, as was also true in the Two Phrase study. For 3-letter words in the PHL pangram – the, fox, dog -- as seen in the Two Phrase study, perception accuracy was consistent between groups; however, words of 4-5 letters saw a difference in tactile perception accuracy between PHL and control users. This result is present in word quizzes, as well as the full quiz (Figure 13b). On the final quiz, PHL participants successfully read 93.3% of the Braille alphabet on average.

Questionnaire

We follow the study with a nine question survey. Seven-point Likert scales are used on some questions (Strongly Agree (7) to Strongly Disagree (1)). Select results are tabulated below.

Question	PHL	Control (did not receive vibration)
"I did not actively pay attention to the vibrations while playing the video game"	7 (x4)	5 (x2), 7 (x2)
"Near the end of the sessions, I didn't pay attention to the vibrations at all"	7 (x3), 6 (x1)	3 (x1), 7 (x3)
"I focused only on playing the video game"	7 (x2), 6 (x2)	7 (x2), 6 (x2)

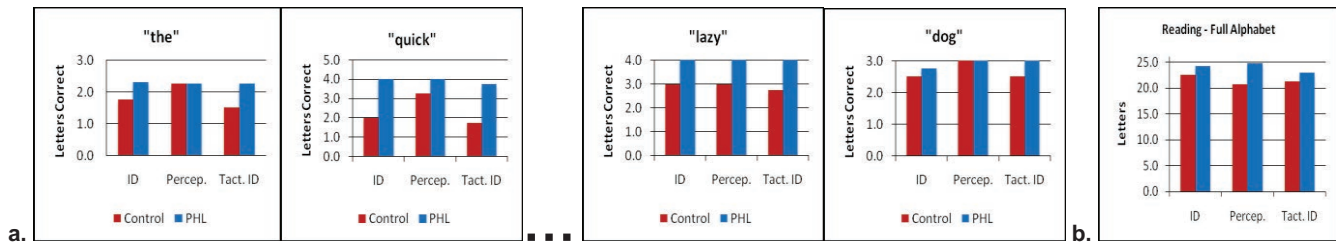


Figure 13. (a.) Reading scores for mini-sessions 1, 2, 7 and 8's quizzes. Here, ID is visual Braille reading, 'Percep.' is tactile perception and Tact. ID is tactile reading score. (b.) Full Braille reading quiz results. Red remains Control, blue is PHL

DISCUSSION

In this expansion of our validity study, we see that users receiving Passive Haptic Learning dominate throughout learning to type the full Braille alphabet and reach 0% typing error within four hours. Results indicate that those with PHL were able to learn words passively, and complete learning more quickly. We see that all users were able to learn actively some letters through trial-and-error during the tests, and we project that those with PHL reached 0% error rapidly by needing only to actively learn a few unknown letters (i.e. 'z' before they were passively taught 'lazy') because other letters they encounter on the tests were known from passive learning.

Full study results also suggest that typing practice can also act as reading practice. Those receiving PHL again **read more** than those with only control (active practice). The gap in perceptive ability in those without Passive Haptic Learning is unexpected though. What is the reason for this added benefit from PHL? Perhaps those experiencing Passive Haptic Learning are able to match what they sense with their expectations and knowledge of the letters. What these results mean to future Braille instruction methods is yet unknown.

Because of the informative feedback used during the lengthy tests in this study, users were able to 'pick-up' how to type letters during the tests. This study was thus somewhat a comparison of active typing practice (AP) and PHL. Results strongly support the promise in a system for Passive Haptic Learning of Braille typing (and reading). This system shows promise to reduce time and difficulty for people learning Braille.

One of the most cited causes for the crisis in Braille instruction is the growth of technology [1, 2, 10]. The idea that schools can neglect literacy instruction because of screen readers or audio recording is ubiquitous. Perhaps work in wearable, tactile interfaces and Passive Haptic Learning can redefine technology as a solution, rather than a cause of the problem.

FUTURE WORK

We now work to perfect the system to maximize its effectiveness in teaching Braille typing and reading. We will continue to streamline the design to make it increasingly mobile and embrace the results of our concurrent perception studies to make the haptic interface ideal for ease-of-use. We will leverage results presented here to better understand how this system can help and how to best apply it to the populations that need it and contribute to solving the Braille literacy crisis.

A subsequent goal of this research is to develop a system that aids in learning stenotype, a text entry technique used for real-time transcription. Similar to Braille, stenotype is also a chorded text entry system. Considering the similarities in typing Braille versus Stenography, expansion of our current system to passively teach stenotype appears achievable. Passive Haptic Learning of stenotype would aim to reduce exorbitant practice time for experts and lower the barriers to entry into this industry – with current vocational school dropout rates of 85%-95%.

CONCLUSION

Here we present a system and two studies. In the first, Passive Haptic Learning of chorded text entry, Braille, is examined for validity and found to be robust. Users aided by passive learning can increase accuracy at typing a phrase in Braille by 32.85% vs. 2.73% average decrease without PHL. These participants also gained reading skills through their passive learning of typing, ultimately able to *recognize and read* 72.5% (vs. 22.4%) of Braille letters from the phrase. In the second study, we passively teach the full Braille alphabet over four sessions. Participants receiving PHL increased accuracy more rapidly and consistently, with 75% of PHL vs. 0% of control users reaching zero typing error. By the end of the study, PHL participants were also able to *read* 93.3% of all Braille alphabet letters.

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