Passive Haptic Training to Improve Speed and Performance on a Keypad

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Learning text entry systems is challenging, yet necessary. Many layouts and keyboards exist, but they rely on laborious learning techniques. Passive haptic learning (PHL) has already demonstrated some benefit for learning the Braille text entry system. Could this computing-enabled technique be used to improve desktop keyboard typing skills? It is unknown whether passive haptic training can improve speed on a motor task (as opposed to initial learning). We use a randomized numeric keypad to examine users' typing performance with or without passive haptic training. When users were prevented from looking at the keyboard, the PHL group demonstrated consistent accuracy (-0.011 KSPC) while those in the control group greatly increased their error (+1.26 KSPC on average). This result is consistent with the finding that PHL users looked significantly less at the keyboard. In a second, longer study, users exposed to PHL were found to significantly improve their typing speed (mean increase of 11 WPM) versus control (mean increase of 2.2 WPM).

Additional Key Words and Phrases: Wearable, Haptic, Text Entry, Learning, Keyboard, Typing

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1 INTRODUCTION

Learning text input systems is challenging, and teaching techniques rely largely on repetitive typing practice that frustrates learners [3, 39]. More efficient layouts and keyboards may exist, but they often rely on the same laborious learning techniques. For example, a high school typing class may require 40-60 hours of QWERTY transcription practice and expect highly performing students to reach speeds of 40 word per minute (WPM) [11, 12, 27]. As another example, stenotype students must spend years practicing to achieve the 180 WPM required for courtroom reporting, and over 85% of courtroom reporting students will not complete their training [10, 16]. Once a system of typing is learned, users are also reticent to learn other typing systems; even inspiring work on creating partially optimized layouts that resemble the familiar QWERTY [1, 24]. Most typists will never learn DVORAK even though they may believe it is faster than QWERTY [26].

We seek to lower these barriers through passive haptic learning. Passive haptic learning (PHL) is a technique that can help users learn a text entry system [30]. While a person is engaged in other tasks, tactile stimulation

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can deliver instruction on how to perform a skill. The user does not need to attend to the stimulation, and after the "passive" learning they retain sensorimotor memory that enables them to perform that skill. For example, initial research on this technique taught users how to play a song on the piano. Users wore haptic gloves while they took standardized tests. They listened to a short song on repeat while the gloves "tapped" the corresponding finger to play each note. Although users focused only on the test, at the end of the study they were able to play the song without wearing the gloves [13]. This technique also helped users learn to type the Braille system, demonstrating passive learning of a text entry skill [30].

Previous research on PHL only used systems with simple key layouts with one key per finger; however, most keyboards have multiple rows of buttons, and each finger needs to control multiple keys. Can PHL still help? How can the necessary finger movements be trained passively? This question is also relevant to haptic training of other motor tasks, such as dance.

In text entry, speed is a key to performance, but it is unknown if PHL can affect speed on a motor task. Both numeric keypads and QWERTY keyboards have each key labeled with the corresponding symbol so that even a novice can begin typing accurately immediately. However, typing by "hunt-and-peck" limits entry speed. Can tactile training improve typing speed over time? Such questions have not been examined in previous work, but if these goals are feasible, many applications from data entry to dance may be augmented using passive haptic training.

To answer these questions, we study entry on a numeric keypad. The numeric keypad is the simplest commonly available keyboard where each finger controls multiple keys. It requires only one hand, reducing the amount of hardware needed for testing. Numeric data entry is a task that has been well covered in the literature making it easier to study in laboratory conditions. In addition, while not as ubiquitous as the need for QWERTY text entry, fast numeric data entry is still a required skill for many jobs, and a method of increasing learning speed could be beneficial to schools that teach those skills.

Here we examine these questions. In two experiments containing 12 and 14 participants respectively, we examine entry performance on a randomized, multi-row keypad when augmented with passive haptic training. In this paper, we:

- Demonstrate passive haptic learning of a numeric keypad
- Show that passive tactile training can improve speed on a motor task (numeric entry)
- Convey and teach movements (multiple keys controlled per finger) through passive stimulation
- Suggest a wearable computing solution for learning *and improving* keyboard typing skills

2 BACKGROUND

2.1 Keyboard Learning

Current techniques for learning the desktop or similar keyboards are often limited to active practice. Conventionally, users wishing to improve their skill perform typing drills or games [3, 39]. This repetitive practice of a motor skill is the state-of-the art to achieve automaticity [34]. Research has been done on the learning curve that characterizes this learning process for QWERTY [6, 23] and other keyboards [5, 22, 25], and even cognitive models have been developed to simulate it [6, 7]. Text entry learning is a well-defined problem [5, 22, 25]. Many "crutches" exist, such as auto-complete and search suggestions, to boost interaction performance despite these learning challenges. Research on interventions for improving keyboard learning is mostly limited to keyboard setup while using tutoring software and instruction timing in schools [3, 4, 27, 28, 38]. Most other research suggests different keyboard layouts, but with the same laborious learning methods [22, 25].

Most text entry research in haptics focuses on tactile *feedback* (such as a vibration each time a key is tapped) to benefit in-situ typing performance as opposed to impact learning [2, 18]. Other haptics research uses haptic *cues or guidance* during motor tasks like typing [20, 21, 35]. Since these cues are presented during task performance though, they may only serve to be a crutch to participants and have demonstrated mixed results on facilitating learning and performance.

2.2 PHL and Haptics

Haptics is the domain which investigates touch and tangible interaction. Haptics research has led to devices that provide this tactile feedback using techniques including vibration (most commonly), skin-drag, electrostimulation, and light touch, among several others [15, 36, 37]. Each of these techniques have their advantages and disadvantages regarding hardware, wearability, interaction and resulting perception. Vibrotactile actuators are used in this paper's research because they are straightforward to drive, robust for integration into wearables, can be tuned to strongly stimulate the Pacinian corpuscles (mechanoreceptors in the skin), noninvasive (as opposed to electrostim) and backed by previous research in Passive Haptic Learning [31].

Passive haptic learning (PHL) is an application of haptics for motor skills. Unlike active cues that occur while someone is performing the task (i.e. typing), haptics can be used to help individuals learn "muscle memory" before they start performing. Research on passive haptic learning has demonstrated a number of things about the technique, but it is unknown whether PHL can convey movement and multiple states to a user, or whether tactile training can impact speed. Initial work on PHL for piano demonstrated that simple *one-finger-controls-one-key sequences* could be taught passively [13, 14, 17, 31]. To expand upon this work, Braille typing was taught with passive haptic learning which showed that *discrete, chorded* actions could be conveyed though PHL [30, 33]. Most recently, research has shown that *rhythm* can be conveyed passively though haptics [32]. No research has been done on haptics for a multi-row keyboard like QWERTY however. In addition, these studies only considered accuracy of the skill, not performance speed. Can haptics train movements of the fingers, even without the user's attention? Can passive tactile training impact typing speed over time?

These questions are unanswered in the haptics literature. Haptic training has been explored to teach movements, but research remains in an active capacity – usually using kinesthetic guidance and often for rehabilitation [8, 9]. Williams et. al. produced a review of haptic training research, and better defined the areas of haptic training, haptic cues, and haptic guidance [41]. Examples of related haptics guidance or cuing research include guidance in visual search and spatial manipulation [19, 40]. These areas of research inform our work for spatial learning, but passive training of movement outside of task performance is unexplored. In addition, most research on haptic training focuses on accuracy metrics, and improvement on task performance speed is largely uninvestigated [42].

3 PILOT STUDY

We wanted to know if passive tactile stimuli could aid in the learning of keyboard typing. To examine the potential in this theory, we first studied whether users could improve typing performance on a reduced keyboard with the aid of passive haptic learning. We recruited 12 participants for this study (18-25 years of age, 6 male/6 female).

The reduced keyboard used here is the 4x3 number pad, which is typed in the same way as the QWERTY keyboard but uses only the right hand. Since most individuals have varying, non-negligible skill at desktop QWERTY typing we use a randomized mapping in this experiment. Unlike in previous research on passive haptic learning, the keyboard being learned here is labeled (as are most QWERTY keyboards); this labeling enables users to look for the correct key to type. To provide more information on this behavior in our study, we use an eye tracker during typing tests.

Will users exposed to PHL show higher typing speeds? Can PHL help users learn, even on a grid-shaped keyboard where each finger must control multiple keys? We hypothesized that users exposed to PHL will demonstrate higher typing speeds on this task.

Users were randomly assigned to either the passive haptic learning or control condition. Each user visited the lab for one session with the structure in Table 1.

Fig. 1. The keypad and randomized layout.

PHL	Control
Pretest	
Distraction task and passive stimuli (15 min) top row	Distraction task (15 min)
Test 1	
Distraction task and passive stimuli (15 min) mid. row	Distraction task (15 min)
Test 2	
Distraction task and passive stimuli (15 min) bot. row	Distraction task (15 min)
Test 3	

Fig. 2. Session structure. All users have the same tests and same distraction task.

3.1 Distraction Task Periods

During the 15-minute distraction task periods users sit at a desktop computer and play an online memory game. This game was chosen as a metric for distraction and is used in other research on passive haptic learning [30]. All users are asked to pay attention only to the game and focus on getting a high score. Users in the passive haptic learning condition also wear a computerized glove and earbuds during this time which provides the stimuli to passively “teach” them. They are told that this stimuli is related to their typing tests, but again to pay attention only to the game.

3.1.1 Passive Stimuli.

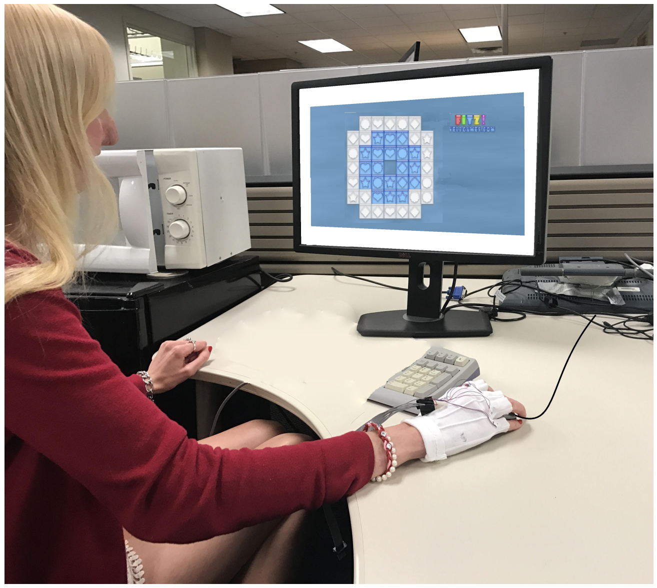

Fig. 3. The apparatus used in the distraction tasks. (Game image on screen was digitally enhanced for this photo)

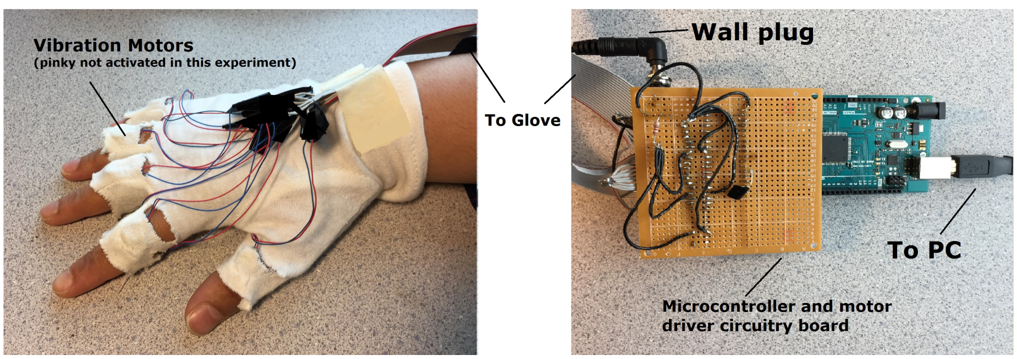

Fig. 4. The wearable computing glove used to provide haptic training.

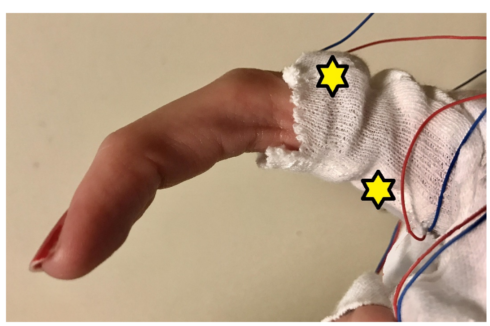

Fig. 5. The top and bottom vibration motor locations. Stars highlight these locations on the example finger.

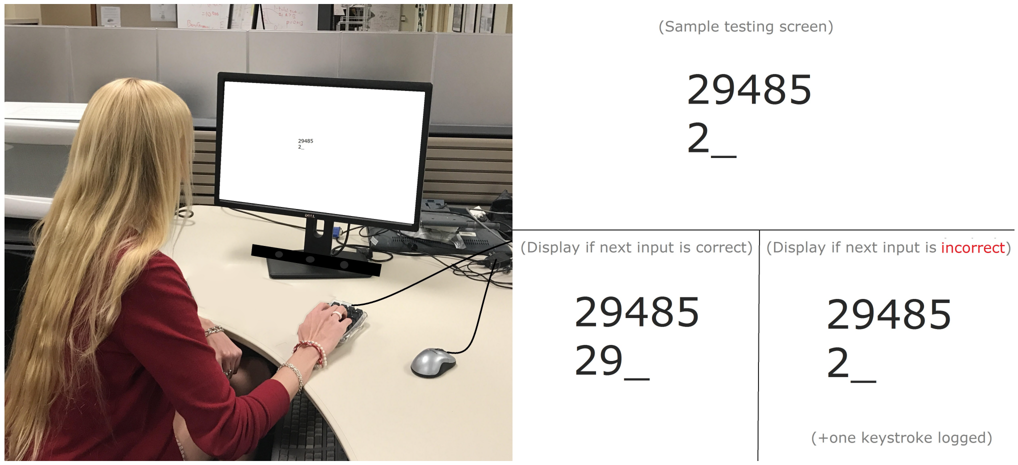

Fig. 6. The setup for testing sessions.

3.1.2 Passive Stimuli. The glove is fingerless for improved fit on a variety of hand sizes. A small, coin-shaped vibration motor (Precision Microdrives 310-113) is attached to the top and bottom of each finger and these are driven by a small circuit board. These eccentric Rotating Mass (ERM) motors are driven with 3V DC to provide the constant current required for peak recommended vibration strength (1.38 G) and a 220 Hz vibration frequency (frequency increases proportionally with applied voltage). The motors are driven by TI ULN2003 Darlington array chips to provide the necessary current and buffer the system's microcontroller.

During each distraction task period, users passively "learn" one row of the randomized keypad shown in Figure 1. The keyboard's mapping is the same for all participants. Teaching a row at a time allows for "chunking" [29] and infers an already-present spatial grouping both of which benefit spatial memory and may make learning easier. The numbers in this row are repeatedly spoken on a loop (using a previously recorded text-to-speech voice) with 7-second pauses between repetitions. Immediately after a number is spoken, a vibration "taps" the correct finger used to type that number key. Vibrations are sequential with offset of 100-300ms and duration about 500ms. For keys in the upper row, the motor on the top of that finger vibrates. Similarly, for keys in the bottom row, motors on the bottom of the fingers vibrate. If a key is in the middle row, both motors vibrate. The large key on the bottom of the keypad (here labeled 6) is operated by the thumb and taught along with the bottom row. The pinky finger is not needed for typing on this keypad and is therefore not stimulated.

3.2 Typing Tests

Tests gauge users' typing performance on the randomized keypad. They are given a pre-test at the beginning of the session and a test after each distraction task period (when PHL users passively "learn"). During all tests, users sit at a desktop computer and type on the keypad with the right hand. They are asked to type whatever prompts appear onscreen. The prompt corpus for each test is five randomized strings containing all numbers on the keypad (0-9), presented in 5-character halves. Proper hand position is enforced by the study observers in both studies: participants must use the correct finger to type each key. They are told to use the index finger for the leftmost keys, middle finger for the middle row, ring finger for the rightmost keys, and the thumb for the long bottom key. All participants (including control) are observed and corrected if they deviate from proper fingering. Error correction is not permitted, but successful entry of each character is required to move forward. If an incorrect character is entered, nothing new appears on screen but the keystroke is logged. This technique

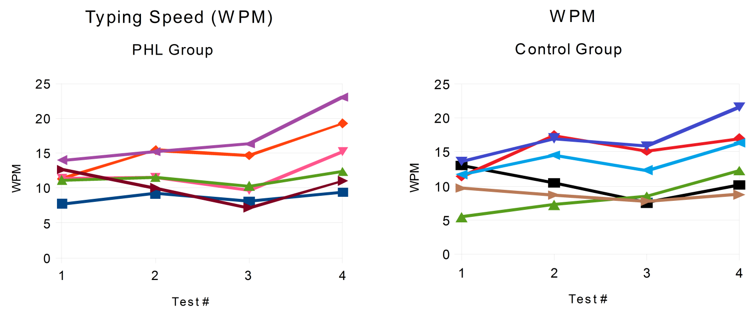

Fig. 7. Typing speed by user group across tests in the first study. Each line is one user.

allows us to focus on speed. We use a Tobii EyeX eye tracker to monitor when participants are looking at the keyboard. To allow natural looking behaviors to emerge, participants are only told that the goal is to look less at the number pad and type with good skill.

3.2.1 Bonus test – keypad obscured. For four participants (2 PHL, 2 control), we included a additional test at the end of the session. This test had the same structure and content as the others, but the participant's hand and the keypad was covered by a paper screen. This test was intended to reveal differences in knowledge of the keyboard layout.

3.3 Results

Typing test software logged user responses, timing and eye tracker data. Errors, counted as extra keystrokes per character (KSPC), remain consistent for each user throughout the session and similar between groups (between Means=1.2-1.3 KSPC, SE=.08-.1 for each PHL group test; Means=1.1-1.2 KSPC, SE=.03-0.1 for control users (repeated measures ANOVA: $F = 4.6$, $p > 0.5$)). No significant difference was found in distraction task scores (unpaired t-test $t(10)=1.00$, $p=0.34$). Both groups increase their typing speeds, calculated as words per minute (WPM), from the beginning to the end of the session (PHL: M=11.4 WPM, SE=0.85 to M=15.1 WPM, SE=2.12; and Control: M=10.8 WPM, SE=1.2 to M=14.3 WPM, SE=1.8), but any difference between groups was not significant (unpaired t-test $t(10)=0.06$, $p=0.95$). Time spent looking at the keys decreases some amount over time in both conditions. In particular, the number of looks decreases significantly for users receiving passive haptic learning (repeated measures ANOVA: $F(5, 3) = 23.23$, $p < 0.05$). On the contrary, those in the control group show no significant reduction in looks at the keyboard (repeated measures ANOVA: $F(5, 3) = 1.297$, $p > 0.05$). When the keyboard was obscured for the bonus test, the two users in the passive haptic learning group demonstrated consistent error rates with their uncovered performance (increase M=0.022 KSPC). The two users in the control group, however, showed an increase in error when they could not look at the keys (increase M=0.45 KSPC).

3.4 Discussion

Results suggest that passive haptic learning has an effect on learning this task. It was unknown whether a skill involving multiple states (keys controlled) by each finger could be augmented with tactile stimuli, but differences in metrics between groups seem to indicate that those receiving PHL had different knowledge of this skill. Error remained low for all participants, likely because the keyboard layout was labeled. Those receiving passive haptic learning looked at the keyboard less than those in the control group however; suggesting that PHL users had more certainty in their internal knowledge of the layout. Results of the few trials at the "bonus test" also indicate

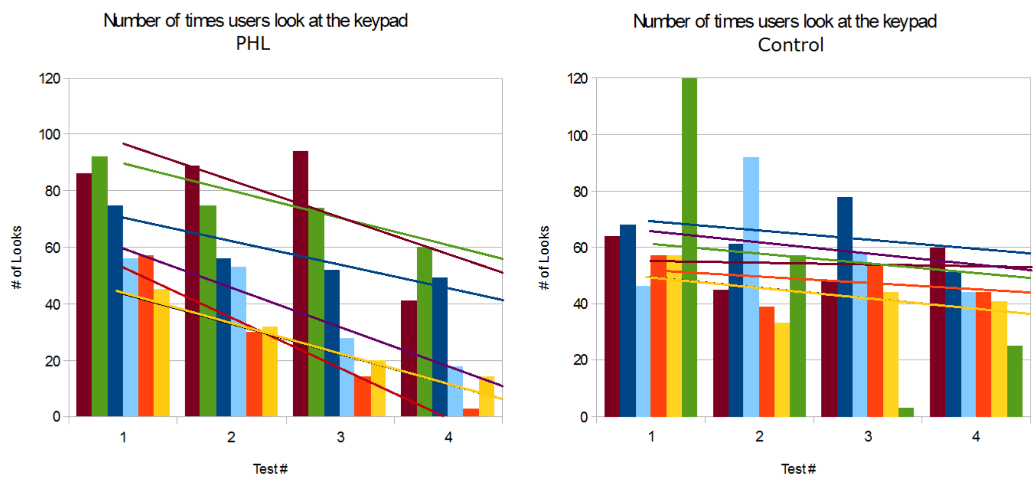

Fig. 8. Number of looks at the keyboard for each test. Each color bar/trendline is one of the 6 users in that condition group.

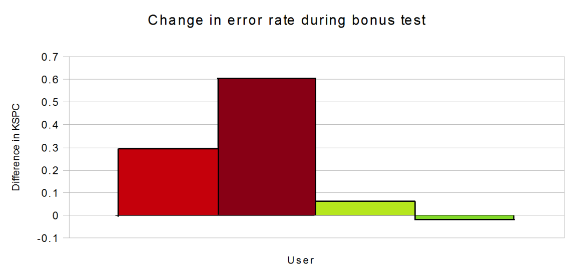

Fig. 9. Average increase in errors per character in the bonus test of the pilot study. PHL group users are in green (right) and control group users are in red (left).

this trend; when control group users could no longer reference the layout visually, they doubled or tripled their error. PHL users, however, showed no increase in error when they could not see the keyboard – suggesting that these users know the layout. These results indicate that passive haptic learning may help users pick up this skill more quickly and encourage further research on PHL for keyboard typing. Although differences in speed between groups were not significant after this single session, results on learning were encouraging. It is possible that speed differences may emerge after users have practiced the skill for longer, so we next conduct a lengthened version of this study to examine for longitudinal trends in keyboard typing performance with passive haptic learning.

4 LONGITUDINAL STUDY

We next conducted a multi-session study to examine for speed differences in non-novice users. Can passive haptic learning help users become faster at a skill in less time? We hypothesize that after three sessions users exposed to PHL will demonstrate faster typing speeds than those in the control group. We recruited 14 participants for

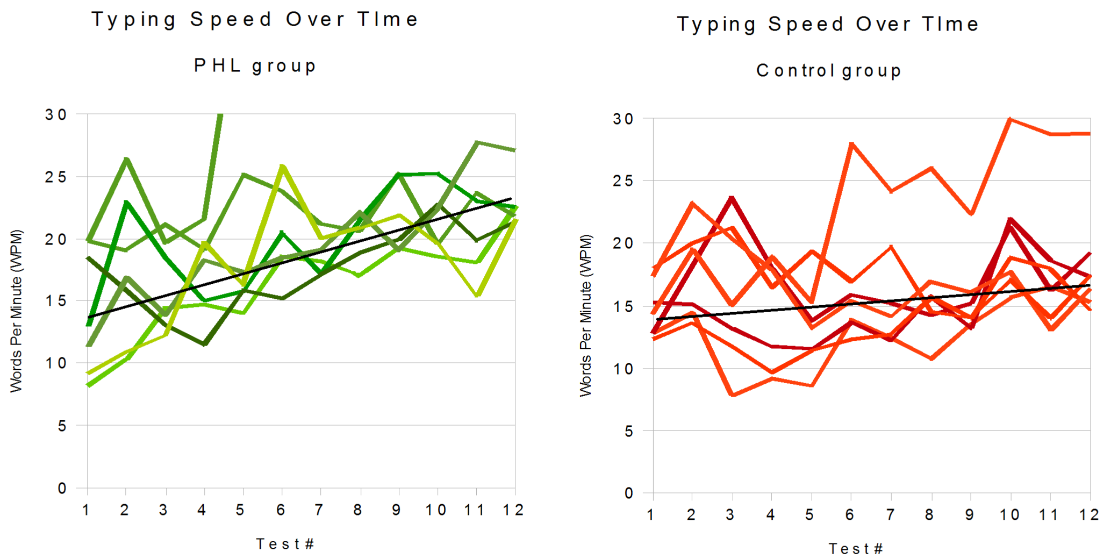

Fig. 10. Typing speed on each test including group trendlines. Shows changes in speed over time. Each line corresponds to a user. One line is truncated for scale (PHL user reaches above 30 WPM at session 5 and remains above this pace).

this between-subjects study (18-24, 6 Male/ 8 Female) and randomly assigned each to either the passive haptic learning or control condition.

This study consists of three sessions, 5-24 hrs apart. Each session is identical to the structure used in the first study, except all sessions here include the bonus test at the end.

4.1 Results

Typing and eye tracker data was logged by the testing software. Errors (keystrokes per character (KSPC)) remain consistent and low during tests other than the bonus test throughout all sessions. No significant difference was found in distraction task scores between groups (unpaired t-test t(10)=0.6926, p=0.51). Change in typing speed was evaluated as difference in words per minute (WPM) from the initial pre-test to the last "test 3." Users exposed to passive haptic learning showed a significantly greater increase in their typing speed: 11 WPM faster on average versus 2.2 WPM for control (PHL SE=2.1 WPM; control SE=1.5 WPM; unpaired t-test t(12)=3.32, p=0.0061).

The speed differences found between groups are also found in the trends across all tests (repeated measures ANOVA for a difference in trend between groups: F(12, 11)=22.06 p <0.0001).

We also evaluated the number of times that users choose to look at the keyboard during each typing test. Both groups look at the keyboard about the same number of times at the start of the study (M=71, SE=7.2 for PHL vs M=77, SE=10.2 for control) per test, but by the end of session one, PHL users significantly reduced their average number of looks per test (M=42). Number of looks per test was compared between the beginning and end of the study. Users exposed to PHL reduced their looking at the keyboard significantly more than the control group (unpaired t-test t(12)=2.56, p=0.0246) ending at M=31, SE=7.4 for PHL vs M=48, SE=8.2 for control for the last test.

Control group users showed higher error during the bonus tests. On the bonus test at the end of session one, the difference is most apparent: Control users showed an average increase of 1.26 KSPC (SE=0.71). PHL users had

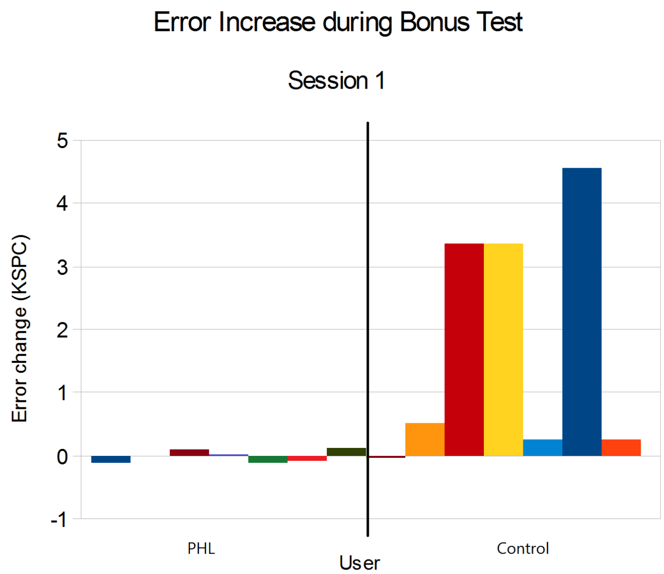

Fig. 11. Increase in error when users could not look at the keyboard. Bars left of the line represent error scores for users in the PHL group, bars right of the line are control group users.

a negligible -0.011 KSPC average change in error when the keyboard was obscured (SE=0.0037). The difference was not quite statistically significant due to variance in control user 1 (unpaired t-test t(12)=1.84, p=0.09).

4.2 Discussion

Results in the longitudinal study are consistent with those of study one and also expose new trends. After the first session, where most change occurs, more differences in typing performance between groups become apparent.

Data from this study indicates that PHL has positive effects on learning metrics, congruent with differences found in study one. Error remains consistent and low throughout all sessions in this study, likely because of the labeled keyboard layout. PHL group users once again look significantly less at the keyboard as time goes on. Control group users maintain the same level of glances at the layout. These results indicate that those exposed to passive haptic learning feel less need to reference the labels, suggesting that they know the layout better. Initial looks from PHL participants are also more searching/orienting in nature (longer average looking duration), whereas the control group is observed to rely on many quick glances throughout the study. The bonus test results also suggest this difference in knowledge between groups. When control group users were not permitted to look at the keyboard during the bonus tests, most demonstrated large increases in error. Consistent with the pilot results of this test during study one, PHL users showed negligible change in performance when they could not see the keyboard. These results suggest that those exposed to passive haptic learning are more familiar with the layout. This difference between groups was greatest during session one. The control group improved some on the bonus test in session two and three, likely due to gradual learning of the layout through practice; however, the PHL group continues to out-perform the control group on other metrics (such as speed) during these sessions. Does this suggest that performance differences in sessions two and three are due to motor skill rather than just layout knowledge?

Results also indicate that PHL had an effect on typing speed. Users who had passive instruction demonstrated statistically significant and functionally different increases in typing speed. What does that mean for keyboard learning? We suggest that passive haptic training, facilitated by wearable computing, may be a beneficial aid to learning and improving typing skills.

5 FUTURE WORK

Our ultimate goal is to help users improve their skill at typing on the physical QWERTY keyboard. We are currently building upon this work to create computing systems to teach QWERTY typing and stenotype. The learning system and structure presented here is largely functional, but may be slightly modified as the system is expanded to teach the full keyboards. Should we teach users the layout by row as we do here? Can we teach frequent words or letter transitions (trigrams)? Other projects, such as haptic systems for dance instruction, may also leverage the findings presented here in that combinations of vibration motors may be used to cue different actions.

Some considerations remain in user recruiting and when to intervene for QWERTY learning. Those under the age of 22 (prior to much professional practice) may be novices with physical keyboards but have knowledge of QWERTY from using soft keyboards on mobile phones. Those in an older subset of the population may lack experience altogether. Both of these groups may contain many individuals who use the hunt-and-peck method on the physical keyboard. Would PHL afiect these groups difierently? At what level of skill should we intervene for greatest performance benefit?

6 CONCLUSIONS

To characterize the potential benefits of passive haptic training on improving keyboard typing, we conducted experiments focusing on typing on a randomized numeric keypad. We exposed half of users to passive haptic learning stimuli from a wearable computing glove. Typing tests measuring accuracy, speed, and glancing behaviors demonstrated that those users who were exposed to passive haptic training significantly improved speed over time. PHL users reached speeds typical of touch-typing after the third session, while control group users remained in the typical desktop hunt-and-peck-method speeds (<23 WPM) [25] throughout the longitudinal study. When users were prevented from looking at the keyboard, PHL group users demonstrated consistent accuracy, while those in the control group doubled their error. These results suggest that passive haptic learning enabled greater knowledge of the keyboard layout and increased typing speeds. These findings may inform research in haptic training systems for QWERTY typing, other keyboards, and even applications such as passive haptic training for movement and dance.

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