Tactile Taps Teach Rhythmic Text Entry: Passive Haptic Learning of Morse Code

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ABSTRACT

Passive Haptic Learning (PHL) is the acquisition of sensorimotor skills with little or no active attention to learning. This technique is facilitated by wearable computing, and applications are diverse. However, it is not known whether rhythm-based information can be conveyed passively. In a 12 participant study, we investigate whether Morse code, a rhythm-based text entry system, can be learned through PHL using the bone conduction transducer on Google Glass. After four hours of exposure to passive stimuli while focusing their attention on a distraction task, PHL participants achieved a 94% accuracy rate keying a pangram (a phrase with all the letters of the alphabet) using Morse code on Glass's trackpad versus 53% for the control group. Most PHL participants achieved 100% accuracy before the end of the study. In written tests, PHL participants could write the codes for each letter of the alphabet with 98% accuracy versus 59% for control. When perceiving Morse code, PHL participants also performed significantly better than control: 83% versus 46% accuracy.

Author Keywords

Haptic; Wearable; Learning; Mobile; Passive; Text Entry

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Tactile stimuli can help users learn without devoting active attention through a process called Passive Haptic Learning (PHL) [5, 6, 8, 16, 17]. This technique is made possible by wearable computers, which apply the instructional tactile stimuli. Research on teaching Braille and piano using PHL has revealed that sequences of keys can be taught with this technique [16, 17]; however, it remains unproven as to whether information on rhythm can be conveyed passively. Here we use Morse code, a text entry system based upon rhythm, to answer this and other questions about PHL. In addition, previous studies required custom-designed, haptic gloves focusing on stimulation of the fingers: here we use a pre-existing device (Google Glass) to deliver the stimuli to the side of the head.

In this paper, we:

- Demonstrate Passive Haptic Learning of a temporal system (Morse code)
- Use an off-the-shelf device (Google Glass)
- Administer tactile stimuli to a novel area of the body for PHL (the head)

In the process of this study, we also:

- Describe how to create appropriate tactile sensations using the bone conduction transducer (BCT) on Google Glass
- Suggest that PHL might reduce the effort for learning a silent, eyes-free text entry method for small mobile devices

BACKGROUND

Researchers have examined haptic feedback for motor skill training [1, 3, 13, 15, 18] and memory [7, 20]. Most prior research focuses on kinesthetic tactile feedback and active participation by the user. However, learning does not always have to be an active process; it can sometimes be passive. Passive learning is "caught, rather than taught" and is "typically effortless, responsive to animated stimuli, amenable to artificial aid to relaxation, and characterized by an absence of resistance to what is learned" [10].

Passive Haptic Learning uses tactile stimuli to instruct users as they go about their daily activities (passive learning). Previous experiments on Passive Haptic Learning have shown that manual skills such as piano playing and chorded typing can be learned or reinforced using vibration stimuli even while the user is engaged in other tasks [5, 6, 8, 16, 17]. In these studies, users wear gloves with vibrating motors at the base of each finger. As a note plays or a letter is spoken, the appropriate fingers to produce that note or letter are stimulated. Users are instructed to ignore these stimuli and focus on a mentally taxing distraction task such as a standardized test during this time, yet learning of the "muscle memory"

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Figure 1. Left: Morse codes for the letters *A*-*G*. Right: A straight key for producing Morse.

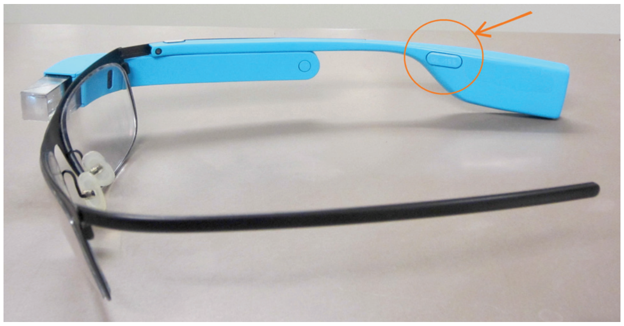


Figure 2. Glass's bone conduction transducer.

still occurs. After PHL, users remove the gloves and perform the skill of interest (e.g., typing Braille). Results are significantly better than for control participants who simply hear the music or spoken letters without the tactile stimulation. In these studies, PHL often results in performances with no errors. While active practice can produce the same results more quickly [8], the mobile gloves designed in the studies mentioned above enable the wearer to be exposed to learning while performing other everyday tasks, allowing a practical means of facilitating learning with little effort and commitment required.

PHL may be used to teach a diverse range of skills from those for entertainment to accessibility, yet much remains to be learned about PHL. In previous research, users were not taught rhythm information passively. For example, passive stimuli helped users learn the sequence of piano keys but not the tempo. One question that remains unanswered is whether PHL can be used to convey rhythm or time-based information.

SYSTEM: MORSE CODE ON GOOGLE GLASS

We chose Morse code to investigate whether teaching a rhythm-based skill is possible using PHL. Each letter of the alphabet in Morse code is represented by a group of dots and dashes and is entered using a keying machine (see Figure 1). The dots and dashes in Morse code are short or long taps on the key (by definition, a dash is three times the duration of a dot). We translate this rhythmic system into haptic cues and incrementally teach the experimental group using these tactile stimuli.

Previous work used specialized gloves to administer tactile stimuli for PHL; however, many modern wearable devices such as smartwatches, mobile phones, and fitness trackers include actuators and could potentially be used instead. For this study, an off-the-shelf Google Glass was selected. Glass can produce both tactile cues and audio feedback using its bone conduction transducer, and Glass's touchpad allows simple input of Morse code. Thus with Glass, only one device is needed for both training and testing in the study. Smartwatches are another potential choice of device as they often have touchpads and vibration motors. However, the perception of tapping during passive learning might be masked by clothing or movement of the arm itself. Therefore, for this initial research, we use Glass which also has the benefit of not requiring an external headset for audio.

One can also imagine using wearables on other parts of the body or using PHL to teach a skill like dance, yet the only body part studied to date has been the hands. Does PHL work on other body parts? Does the part of the body that is being trained to perform a task have to be the same that receives the sensation? Teaching Morse code using PHL, with sensation delivered to the head instead of the hands, is a straightforward way to expand our knowledge about this phenomenon.

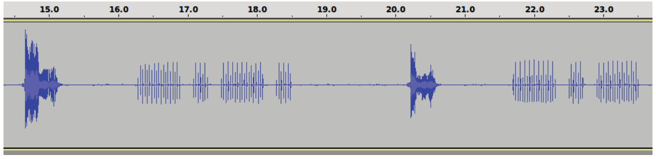
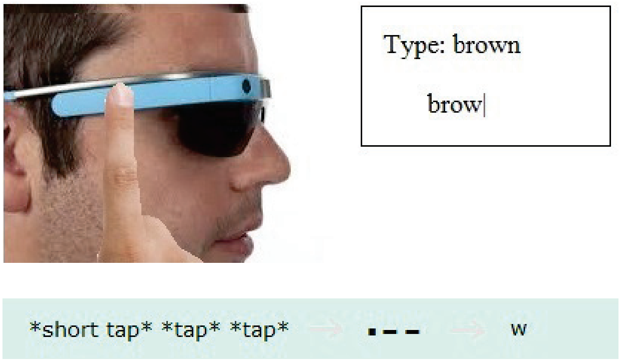


Figure 3. Activation profile for haptic stimuli produced by Glass. Taken using a microphone, this signal shows the letters *C* and *K* spoken, each followed by vibrations indicating their equivalent Morse code (-.-. and -.-).



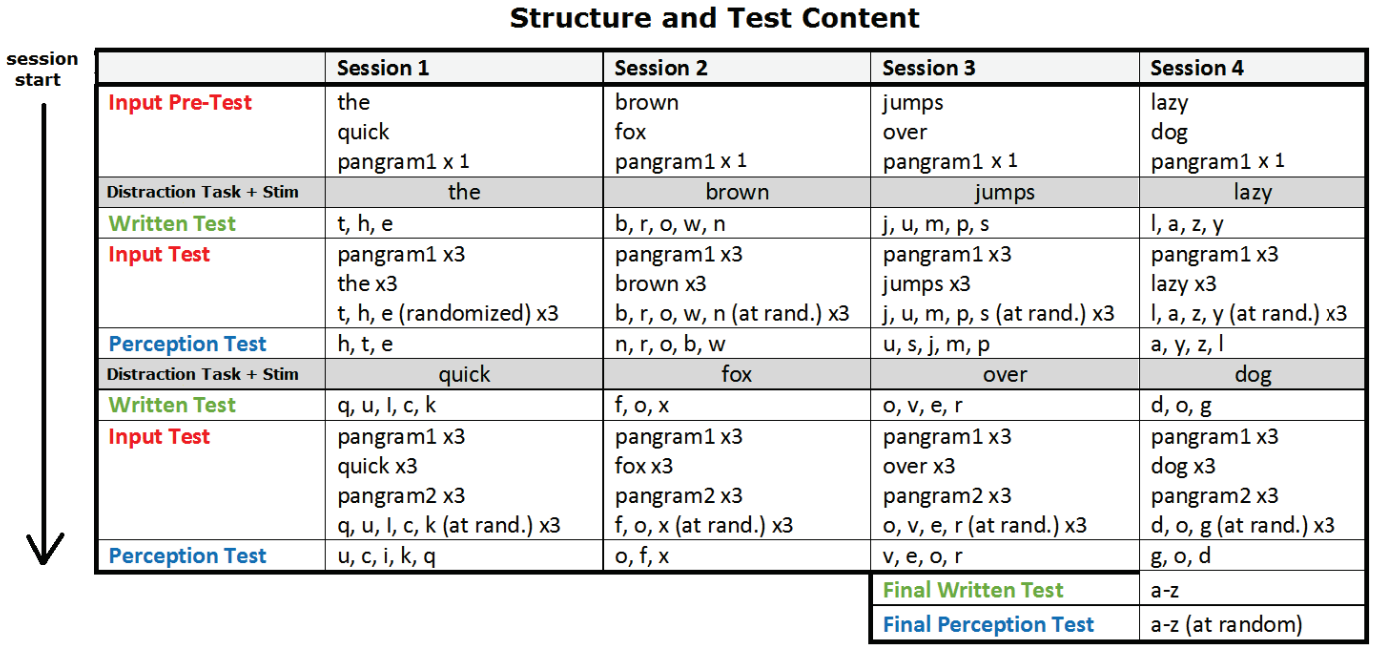
Type: brown

brow|

Figure 4. Left: User tapping Google Glass's touchpad, which runs most of the length of the electronics pod. Right: Example screenshot of Glass's display during input tests. Bottom: The user has just tapped Morse code for the letter *W*.

Creating Taps from Glass's Bone Conduction Transducer

As shown in Figure 2, Glass relies on a bone conduction transducer (BCT) for sound output. We hypothesized that the bone conduction audio system could be transformed to a haptic element by using low-frequency audio signals. We discovered that a 15 Hz square wave sent to the BCT produced a discernible vibration against the head above the right ear. Frequencies over 30 Hz do not produce noticeable tactile feedback, and the quality of feedback seriously degrades



Structure and Test Content

	Session 1	Session 2	Session 3	Session 4
Input Pre-Test	the quick pangram1 x 1	brown fox pangram1 x 1	jumps over pangram1 x 1	lazy dog pangram1 x 1
Distraction Task + Stim	the	brown	jumps	lazy
Written Test	t, h, e	b, r, o, w, n	j, u, m, p, s	l, a, z, y
Input Test	pangram1 x3 the x3 t, h, e (randomized) x3	pangram1 x3 brown x3 b, r, o, w, n (at rand.) x3	pangram1 x3 jumps x3 j, u, m, p, s (at rand.) x3	pangram1 x3 lazy x3 l, a, z, y (at rand.) x3
Perception Test	h, t, e	n, r, o, b, w	u, s, j, m, p	a, y, z, l
Distraction Task + Stim	quick	fox	over	dog
Written Test	q, u, l, c, k	f, o, x	o, v, e, r	d, o, g
Input Test	pangram1 x3 quick x3 pangram2 x3 q, u, l, c, k (at rand.) x3	pangram1 x3 fox x3 pangram2 x3 f, o, x (at rand.) x3	pangram1 x3 over x3 pangram2 x3 o, v, e, r (at rand.) x3	pangram1 x3 dog x3 pangram2 x3 d, o, g (at rand.) x3
Perception Test	u, c, i, k, q	o, f, x	v, e, o, r	g, o, d
			Final Written Test	a-z
			Final Perception Test	a-z (at random)

Figure 5. Session orders and test content. The written test and input test rows demonstrate what users were prompted to write/enter (to test production of Morse code). The perception test row is what was presented to users through vibrations (to test recognition of Morse code).

over 20 Hz. Under 10 Hz produces a signal with clearly discernible oscillations — resulting in poor differentiation between oscillations and Morse code dots. Between 14 Hz and 16 Hz was found to be the ideal range for producing tactile feedback. Peak vibration amplitude at 15 Hz was found to be 1.8 g, as measured by an accelerometer.

Next, we designed the dots and dashes for tapping the user's head in Morse code. Dots and dashes are differentiated by their duration. We assumed that the maximum input speed a novice might reach during our study is 10 words per minute. At that speed dots are expected to be less than 200 ms and dashes are greater than 400 ms. After some informal experimentation, we programmed Glass to represent dots as 200 ms pulses at 15 Hz vibration, and we set dashes as 600 ms in length.

Sensing Morse Input on Glass's Touchpad

Users tap on the Glass touchpad to enter Morse code during input tests. Glass's touchpad (Figure 4) runs most of the length of its electronics pod along the right temple and can sense multiple simultaneous touches. While Glass's multitouch trackpad could allow iambic keying of Morse code, we chose to emulate the more familiar straight-key [14] which is used by simply tapping with one finger.

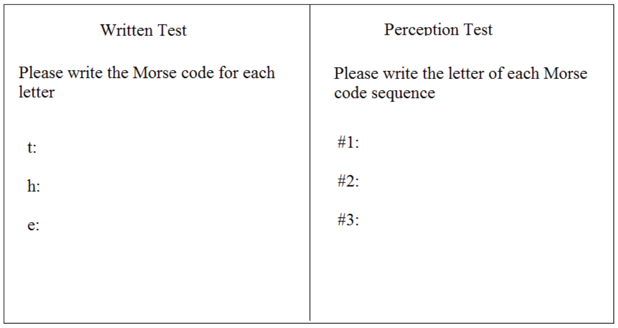
On the touchpad, a quick tap is a dot and a dash is a longer touch. Thus, we chose to interpret taps of 300 ms or less as dots and those of greater than 300 ms as dashes. We decided to use this set threshold rather than have a rolling average threshold that may cause recognition errors by the system and confuse participants with inconsistencies. To leave time for a user to think about the dots and dashes that comprise each letter, the system waits for 1200 ms of inactivity before committing and displaying the resulting letter. These choices still seem adequate in retrospect after the study.

STUDY

We recruited twelve participants (7 male, 5 female; 18-25 years old; recruited through university email lists and compensated $8/hr) for a between-subjects study and randomly assigned each participant to either the Passive Haptic Learning or control condition. We hypothesized that passive, instructional stimulation can reduce errors on Morse code post-tests. We administer stimuli while users are focused on an unrelated distraction task, and we expect stimuli to not adversely affect primary task performance (thus remaining "passive learning").

For each of four study sessions, we start participants with a Morse code input test to gauge their level of knowledge. Next the participants perform the distraction task, an online game called Fitz, for 20 minutes. This scored primary task was selected based upon its sensitivity as a metric for distraction and has been used in prior PHL research to gauge a user's ability to focus even while receiving passive stimulation [16]. During this time, participants are told to focus exclusively on the game and achieving a high score and not to pay attention to any stimuli from Glass. During the distraction task:

- All users wear Glass
- Control group users hear Glass repeatedly spell a word via audio (no Morse code information)
- PHL users hear Glass repeatedly spell a word via audio and feel the Morse code of each letter tapped on their heads



Written Test	Perception Test
Please write the Morse code for each letter	Please write the letter of each Morse code sequence
t:	#1:
h:	#2:
e:	#3:

Figure 6. Examples of written and haptic perception test papers.

We use the familiar pangram "the quick brown fox jumps over (the) lazy dog" to teach the alphabet. By passively introducing one word (several letters of the alphabet) at a time, we chunk learning. Users are exposed to one word on a loop every 20 minute distraction task.

Following the distraction task, participants complete a written Morse production test, an input production test, and a perception test, each of which are described in detail below. The session continues with a second period of the distraction task with stimulation for the next word. The session ends with another battery of written, input, and perception tests (see Figure 5). Given the extensive amount of testing, we expect some learning over time due to active exposure to Morse during the tests.

Written Test

This test presents participants with a list of letters from the word to which they were just exposed and asks them to write the Morse code (dots and dashes) for that letter (see Figure 6). This medium most clearly reflects their knowledge of Morse because they do not have to enter Morse code using an unfamiliar method (like tapping). The test is given immediately after the distraction task so that the participant's knowledge is not augmented by any active learning that occurs during the input test (which gives the participants visual feedback).

Users are told to answer what they know, and if they are totally unsure, they should answer with a question mark. At the end of their final (fourth) session, users are also given a written test on the full alphabet. Test content for each session is detailed in Figure 5.

Input Test

Users tap Morse code on Glass's touchpad during the input tests. Because participants must enter answers on the touchpad, the input test reflects both learning of Morse and their skill at tapping Morse code on Glass. Audio prompts (along with visual prompts) tell users what letter to type during input tests (see Figure 4). No corrections are permitted (e.g., backspace). We chose to provide users with visual feedback of each letter they type instead of obscuring this information. While this feedback facilitates some active learning during the testing periods, we endeavor to create conditions conducive to learning (see Figure 4). In addition, if we released this project into the market as an application for Glass or for a smartwatch, we would attempt to aid learning in every way possible. Thus, for ecological validity, we decided visual feedback was appropriate.

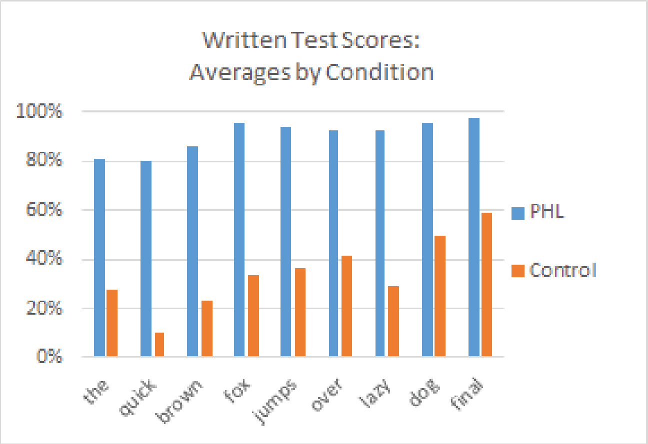


Figure 7. Average score by condition on each written test. "Final" refers to the test of the full alphabet at the end of session 4.

Test content is detailed in Figure 5. Input tests after the second half of a session include three tries at typing a second pangram: "when zombies arrive quickly fax judge pat." This second pangram is included to judge how well participants use their knowledge as opposed to simply learning a set sequence.

Perception Test

Referred to as "coding" in Morse code [14], we also test perception and recognition of Morse signals. The final of the three tests, the perception test is also paper-based and asks users to attend to a series of Morse code vibrations and write down the letters they recognize (see Figure 6). This Morse code is administered at a rate of 10 wpm by Glass and contains only the letters from the word to which the participants were just exposed. Letters are presented in a random order and only played once. Users can pause the system between letters, but many choose not to. The final session of the study concludes with a perception test of all letters in the alphabet in random order.

RESULTS

Significant performance differences were found between conditions, with those receiving Passive Haptic Learning performing better than those in the control group. Performance on the distraction task (Fitz game) showed no significant difference between groups (t(10) =0.424, p=0.372).

Written Test

For the paper-based written test, we analyzed what letters participants correctly answered in Morse. The number of correct letters out of possible letters in the word formed a percentage score for each word's test. We compared the performance of users in the Passive Haptic Learning group versus those in the control group and found significant differences. T-tests reveal that PHL users performed significantly better than control users on all written tests. Mean scores for the Passive Haptic

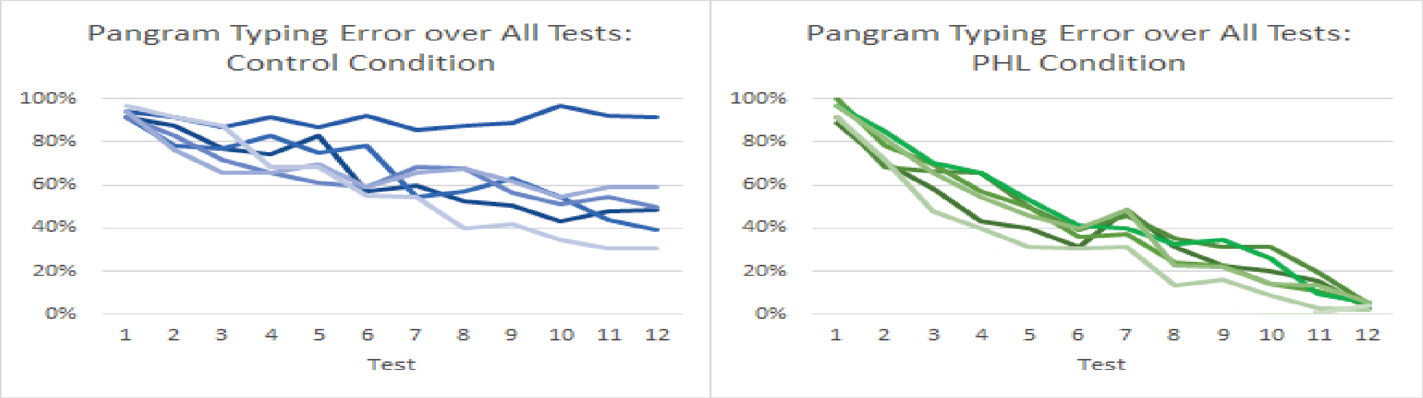


Figure 8. Typing error rates for the full alphabet ("the quick..." pangram) on each input test. Each line represents a user's performance over time.

Learning group ranged from 80-100% for all tests (versus 0-50% for the control group) as shown in Figure 7. On the final test of all letters in the alphabet, PHL users scored a mean percentage of 98.0% correct answers (SE=0.015), whereas control group users scored 59.0% on average (SE=0.102). This difference was again significant (t(10)=3.917, p<0.0013).

Input Test

Accuracy on the input tests was calculated using a Mean String Distance algorithm and used in the Total (Uncorrected) Error Rate metric standard in text entry evaluation [11]. We used these measures to compare the letters that users entered with the prompted string of letters (ground-truth).

To analyze the performance of users over time, we examined error rates on the pangram over the four sessions. The pangram reflects participants' knowledge of all letters in the alphabet (in Morse) and their ability to type them on Glass. We examine the single attempt at typing the pangram given during each pretest and the average of the three trials given during each test. Users who receive Passive Haptic Learning demonstrate different trends in performance over time – with all PHL users reaching lower error scores than all control group users after the first session. We graph these results in Figure 8. A single-factor ANOVA reveals that Passive Haptic Learning has a significant effect on performance (F=54.3, $p<10^{-9}$).

Starting error levels were not significantly different between the groups, but all PHL users finished the sessions with less than 6% error on their final test of the full alphabet (the pangram), whereas the control group finished with a mean error of over 53%.

We also examined error rates when typing the second "zombies" pangram. This result demonstrates users' knowledge and input performance on all letters of the alphabet in a different order than they have been taught. We average the three attempts users are given at typing this pangram during the end of each session (see Figure 9). A single-factor ANOVA reveals that Passive Haptic Learning has a significant effect on performance here as well (F=17.4, p<0.0003). Users receiving Passive Haptic Learning finished with a group average of 7.3% error on their last test (SE=0.013), while the control group had 50.5% mean error (SE=0.082).

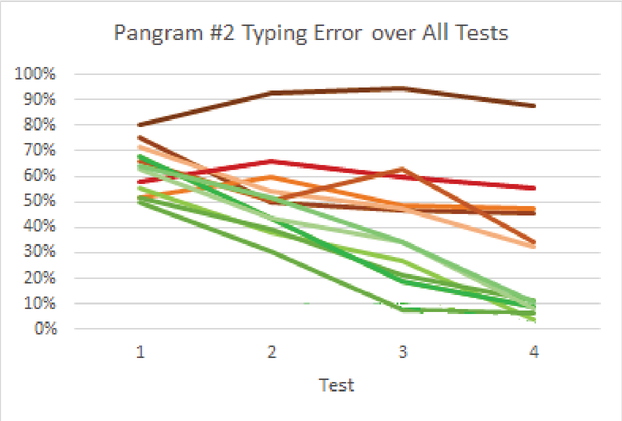


Figure 9. Typing error rates for the full alphabet "when zombies attack" pangram over all four attempts. Each line represents an individual user's typing performance over time. Red lines are users in the control group, and green lines are users in the PHL group.

Participants progressed from initial speeds below 2.5 wpm to nearly 4 wpm when typing the pangram. However, these numbers can be misleading. The system "commit" wait time in this experiment, intended to allow novice learners time to think when inputting the components of each letter, causes reduced speeds. Calculating speeds without the sum of these 1200 ms system pauses shows average entry rates in excess of 8 wpm in the PHL group, which is close to our targeted maximum entry rate of 10 wpm.

Figure 10 shows the shortening of the average duration of a dot and dash over the course of the study. Average dot durations were initially 141.5 ms before converging to 103.1 ms by the final test (SE1=14.5; SE12=4.55). Dash durations began with more variance and a mean duration of 793.8 ms, eventually converging to 543.8 ms (SE1=140.8; SE12=42.4). The 300 ms threshold distinction between dot and dash duration chosen at the beginning of the study continued to be adequate throughout the study. It would be interesting to examine if a lower cutoff time forces faster typing speeds from users in order to comply with the system.

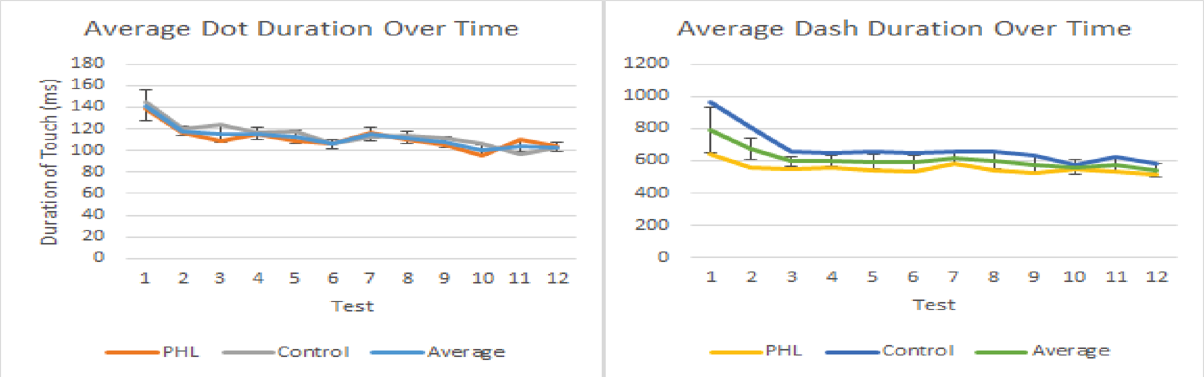


Figure 10. Average dot and dash touch durations over all tests. Standard Error bars are shown on average lines.

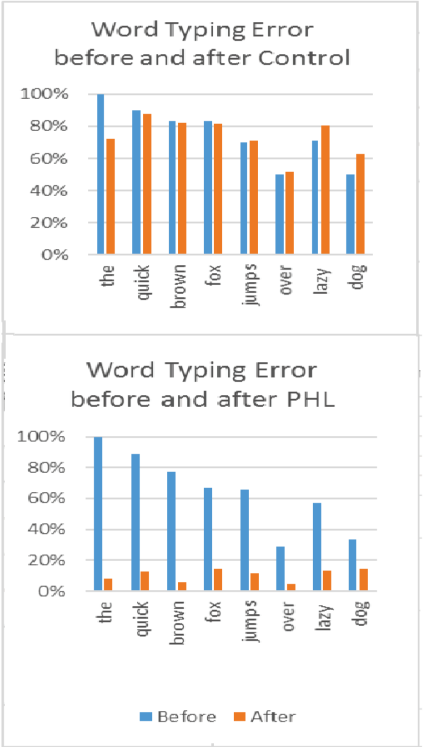


Figure 11. Typing error rate on each word before and after intervention.

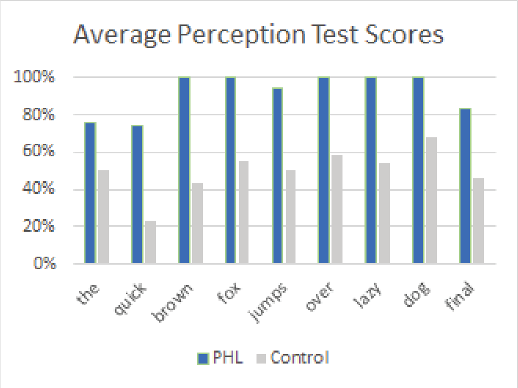


Figure 12. Average score by condition on each perception test. "Final" refers to the test of the full alphabet at the end of session 4.

The difference in typing errors in each word, before and after intervention, was also examined. Users are given one attempt at typing the session's two words during the pretest; after the distraction task (learning period) for that word, users are given three attempts at typing the word during the input test. We compared this first trial with the average of the three post-intervention attempts and found significant improvements after Passive Haptic Learning for all tests. As the left graph of Figure 11 illustrates, there was no significant difference in control group performance (t-test: $t(7)=0.226$, $p=0.414$). There was a significant accuracy difference after users received PHL (t-test: $t(7)=6.06$, $p<0.001$). Mean performance changes between the groups show a difference that was statistically significant for all words after Bonferroni correction (t-tests, alpha=0.05/8).

Perception Test

Users in the Passive Haptic Learning group also performed better on the perception tests. When we analyzed the number of letters that subjects correctly recognized (forming an error score like that of the written test), users in the Passive Haptic Learning group scored over 90% on six of the eight word tests. Users in the control group had mean scores all between 20-68%. This result is illustrated in Figure 12, and t-tests show that there was a significant performance difference between the groups. On the final test of the full alphabet, PHL users were able to correctly recognize 83.3% of all letters presented in Morse code (SE=0.041), while control group users recognize 46.1% (SE=0.076) correctly. T-tests indicate a statistically significant difference in the means between the two groups ($t(10)=4.31$, $p<0.0008$).

DISCUSSION

The results suggest that passive stimulation augmented learning of Morse code. This work cemonstrates Passive Haptic Learning of a rhythm-based system. Each dot or dash stimuli is differentiated not by location on the body but solely by difference in duration. This work also presents PHL of a text entry system very different than the chorded Braille system that was demonstrated previously [16]. Unlike the previous piano research, we are not teaching a motor skill passively, but rather directly teaching a system of meaning through passive stimulation. The area stimulated (the head) is not the body part used to perform the skill (hands tapping Morse).

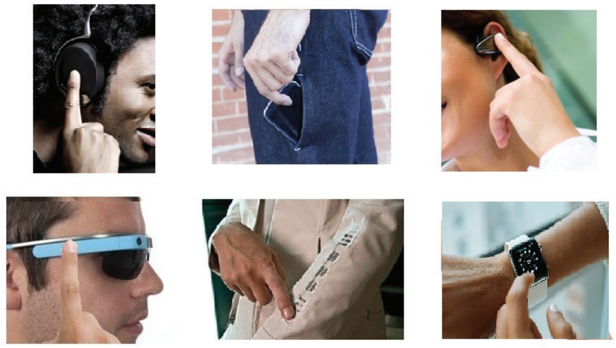


Figure 13. Mobile devices such as earphones, cellular phones, Bluetooth headsets, head-up displays, electronic textiles, and smartwatches may benefit from a silent, eyes-free, small profile text input system such as Morse.

We also use an existing wearable device for Passive Haptic Learning and generate tactile sensation using a bone conduction transducer.

Written test results show significantly better, nearly error-free performance by those who received Passive Haptic Learning, suggesting that the passive instruction helped increase users' knowledge of the entry system.

Input tests indicate learning and reduction of entry errors over time, and results suggest that Passive Haptic Learning also helps users reduce errors more rapidly with little additional active learning or practice. Some active practice occurs during the input tests as we anticipated (when users are provided with visual feedback for the letters they type), which results in some learning over time as indicated by the control group's performance improvement. This active practice during testing is part of the typical method for learning a new text entry system, and the results suggest that augmentation using Passive Haptic Learning could provide significant benefits in this process. User performance typing the second pangram demonstrates the participants' knowledge of the full alphabet. Input performance results for each word show the effects of the intervention, indicating that a relatively short period of passive instruction leads to a large reduction in error. Similar performance on input tests and written tests suggests surprisingly good system usability. Users are keying Morse with relative ease – a potential secondary challenge posed by the input tests. With minor changes to eliminate the per-letter wait time, perhaps the same system could be used longitudinally to increase input speeds. Results show an interesting convergence of users' self-regulated, system-compliant dot and dash durations. Might different system thresholds change user entry speeds?

Perception test results show that users who received PHL performed notably well. Users could receive silent, haptic messages after passive training. Might continued passive stimulation lead to rapid, accurate reception of silent communication too? This concept raises another issue. We taught users by having them receive Morse passively, yet when tested on both reception/perception and production skills, the participants outperformed on production! One explanation for this result may be that the perception test is ephemeral. Participants are only given one chance to hear the stimulus, while for the production tests the participants could control the timing. Even so, this success begs the question: Does exercise in reception rather than production result in better learning?

As an aside, this work also presents an example implementation of silent text input on a mobile device with no keyboard. Overall, users were successful at inputting Morse code on Glass by tapping with one finger. This result suggests that an eyes-free, silent input system can be achieved using a technique like Morse while requiring just a binary sensor. This feature is desired by users of wearable and mobile devices [9, 19], but is increasingly challenging because the streamlined nature of these devices precludes many standard text entry methods. In addition, there are learning costs and barriers that prevent the adoption of many non-QWERTY text entry systems [2, 4, 12]. Perhaps PHL can even be applied to help address the existing challenge for mobile devices and text entry learning.

FUTURE WORK

We demonstrated passive learning of Morse code, but can this technique be applied to increase user performance after initial learning? If passive learning can continue to help mobile users such that they reach speeds over 30 wpm (the speed of hunt-and-peck typing on desktop keyboards), perhaps users might adopt a new text entry system as their main input method. A subsequent investigation might consider if administration of passive stimuli can help users increase speeds and reach the plateau of the power law of practice. Another direction of research is whether users could be taught through audio stimuli alone or haptics alone. Learning on other parts of the body, such as the wrists (using smartwatches), and how these skills transfer to other devices, is also a question.

CONCLUSION

In studying passive learning of Morse code using tactile stimulation from Google Glass, this work focused on researching new elements of Passive Haptic Learning. Results suggest that PHL successfully augmented learning of a rhythm-based system, and stimuli can be successfully delivered on the head as opposed to the hands. The passive stimuli produced significantly increased knowledge of Morse with little additional active learning or practice. Users could input Morse code successfully on Google Glass using just a finger and could understand it silently through haptics. Passive stimuli did not inhibit performance on other tasks – a key component of the teaching method's potential for use during daily life.

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