Mobile Music Touch: Mobile Tactile Stimulation For Passive Learning

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ABSTRACT
Mobile Music Touch (MMT) helps teach users to play piano melodies while they perform other tasks. MMT is a lightweight, wireless haptic music instruction system consisting of fingerless gloves and a mobile Bluetooth enabled computing device, such as a mobile phone. Passages to be learned are loaded into the mobile phone and are played repeatedly while the user performs other tasks. As each note of the music plays, vibrators on each finger in the gloves activate, indicating which finger is used to play each note. We present two studies on the efficacy of MMT. The first measures 16 subjects' ability to play a passage after using MMT for 30 minutes while performing a reading comprehension test. The MMT system was significantly more effective than a control condition where the passage was played repeatedly but the subjects' fingers were not vibrated. The second study compares the amount of time required for 10 subjects to replay short, randomly generated passages using passive training versus active training. Participants with no piano experience could repeat the passages after passive training while subjects with piano experience often could not.

Author Keywords
Haptic, Tactile, Music, Wearable, Passive training

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: Miscellaneous.

General Terms
Human Factors, Experimentation.

MOTIVATION AND RELATED WORK
Playing music can provide many health benefits such as stress reduction, creativity enhancement, and overall enjoyment. Aside from these benefits, playing music also exercises the hands which is particularly important for patients of hand rehabilitation. Playing music can be a fun and engaging activity through which patients can rehabilitate without the ennui that may accompany traditional regimens such as squeezing a foam ball for extended periods. Yet the process of learning an instrument can be time-consuming and often beyond the time constraints of a busy working adult. Beyond the initial learning of songs, practice is required to retain the knowledge. As soon as a new song is learned, forgetting begins immediately [2]. Thus, repetitious practice is needed to retain the new skills. For some musicians with repetitive stress injuries, such practice can, ironically, be hazardous to their career.

However, learning is not always an active process. Much research has been conducted on the phenomenon of passive learning. Passive learning is described as learning that is "caught, rather than taught," and is characterized as "typically effortless, responsive to animated stimuli, amenable to artificial aid to relaxation, and characterized by an absence of resistance to what is learned" [10]. Studies have shown that passive learning of information can occur when subjects are exposed to media rich environments. In a study by Cliff Zukin and Robin Snyder, subjects who lived in a media rich environment and were passively exposed to political information were 40% more likely to have acquired the information than subjects living in a media poor environment [17]. Both subject groups had no interest in the political information.

With the progression of technology in the mobile and tactile fields, a media rich environment need not only be limited to audio and visual stimulation. Research has shown that a multi-modal combination of audio and haptic cues gives the user a richer understanding of musical structure and improves performance of the musical piece [6, 7, 11]. Perhaps a user can be exposed to practice and repetition of haptic skills while engaged in their daily routines (e.g. working at a desk, commuting on the subway, etc.) and can thus reinforce their skills "automatically." We term the phenomenon of acquiring motor skills without active attention "Passive Haptic Learning" (PHL). Note that passive tactile learning, as will be discussed here, would be technically a subset of passive haptic learning. Other researchers have examined

CHI 2010, April 10 – 15, 2010, Atlanta, Georgia, USA

haptic feedback for motor skill training [12, 5, 13, 1, 14] and memory [9, 15]; however most of the work focuses on kinesthetic feedback and active participation by the user.

We have designed a mobile tactile glove stimulation system called Mobile Music Touch (MMT) to explore passive tactile learning of physical skills. Our initial investigations suggest that passive tactile learning may hold potential for learning and rehearsing fingerings for musical instruments, improving typing skills, learning sign language, learning the control of a complicated prosthetic or other interface that requires a sequence of actions, and hand rehabilitation after a traumatic injury. However, before we explore these domains, we first seek to provide evidence of the existence of passive tactile learning in well-controlled, internally valid experiments and learn how best to exploit the effect.

SYSTEM COMPONENTS

The Mobile Music Touch system is composed of two distinct parts: fingerless gloves and a Bluetooth-enabled mobile computing device such as a laptop computer or mobile phone. The gloves are equipped with small vibration motors (Precision Microdrives model #310-101), one for each finger; a Sparkfun Electronics Bluetooth-to-serial module to receive commands from the computing device; and a ATMega8 microcontroller for control (see Figure 1). Fingerless gloves are used to allow better manual dexterity during the wearer's everyday tasks. Figure 2 shows the golf glove used to house the motors and the wireless components. The rectangular black box is a battery pack with 2 AAA batteries. Figure 3 shows a user wearing the glove while learning a song during the pilot study.

With Mobile Music Touch (MMT), users can hear the music and feel the notes on their fingers. Passages to be learned are loaded into the computing device. As each note of the music plays, vibrators on each finger in the gloves activate, indicating which finger is used to play each note. Note that the user could listen to the music using an external speaker, headphones, or a Bluetooth headset.

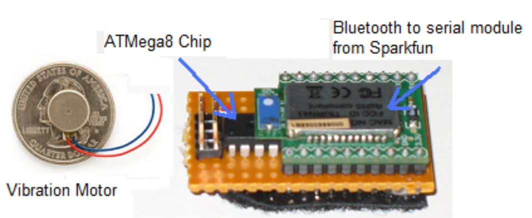

Figure 1. Electronic components of the Mobile Music Touch glove.

Pilot Study and New Contributions

In order to determine if Passive Haptic Learning may be possible with Mobile Music Touch, we performed a pilot study. Four subjects learned portions of Jingle Bells and Amazing Grace using the MMT system and then spent 30 minutes doing a daily task of their choice. During this time, the participants listened to both songs playing in a loop, and one of the two songs provided tactile stimulation. Afterwards, they attempted to play both songs again. Table 1 shows the results.

Figure 2. The Mobile Music Touch glove.

Figure 3. A subject learning a song while wearing the MMT.

Using a paired t-test (two-tailed), the number of errors made between the tactile and non-tactile condition was statistically significant with $p<0.01$. The 95% confidence interval of the reduction in errors performed was between 2.75 to 7.25.

These results suggested that Passive Haptic Learning may indeed be possible. In this paper, we investigate the phenomenon more carefully and report on two larger and more carefully controlled studies. The first study improves and repeats the pilot study to better examine the effect. The second study was originally designed to compare how quickly a passage could be learned with active training versus passive stimulation. However, in piloting the second study an effect was observed which suggested that subjects with a

Sub.	Tactile Song	Non-tactile song	Mistakes tactile	Mistakes non-tactile
1	AG	JB	0	7+
2	AG	JB	0	5
3	JB	AG	0	4
4	JB	AG	3	7

Table 1. Performance of tactile versus non-tactile songs after 30 minutes of task in the pilot study. Subject 1 could not continue after seven mistakes in the non-tactile song. AG=Amazing Grace. JB=Jingle Bells.

musical background would perform significantly differently than subjects without a musical background. The study was re-designed to compare these two conditions directly.

EXPERIMENT 1: AUDIO & TACTILE STIMULATION VERSUS AUDIO STIMULATION ALONE

The primary goal of the first experiment is to show the feasibility of passive haptic learning (as opposed to the more specific goal of learning the piano). Thus, we have improved our pilot study design to be more internally valid and avoid some potential confounds previously observed. Specifically, in this study

1. each subject is tested on a standard reading comprehension task,
2. the songs are newly composed musical phrases to ensure equal unfamiliarity by all subjects,
3. performances are automatically captured by a MIDI keyboard and analyzed using a Dynamic Time Warping algorithm,
4. the newly composed melodies use only 5 keys so that lateral movement of the hands is not necessary,
5. subjects "learn" the melody through MMT after having heard it once as opposed to learning to play a melody correctly on an actual piano keyboard and then having it be reinforced by MMT.

We tested 16 subjects with no piano experience in a within-subject experiment. The subjects consisted of 12 males and 4 females and had an age range of 18-36. To ensure equal unfamiliarity with the songs among the subjects, two new musical phrases were composed for this study. The phrases are shown in Figure 4.

Figure 4. Two new phrases composed for the study.

Both phrases are of novice difficulty, and they were designed to be of similar length while retaining distinctly different melodic qualities. To avoid the issue of lateral movements of the hands, the melodies were composed to use only 5 keys (C, D, E, F, G - see Figure 5). In this way, the glove can provide all the information needed to play the phrases without the user moving his hand up and down the keyboard. While lateral hand movement is typical while playing piano and was part of our pilot study, we wanted to avoid this potential confound to the subject's performance. In the pilot study, where users learned Jingle Bells and Amazing Grace, users reported that knowing which fingers to use provided "hooks into memory" for which keys to press. Thus, while this study focuses on internal validity, we would like to conduct a study in the future with more external validity to study PHL effects with more complex songs.

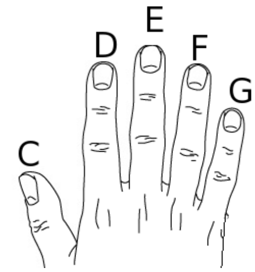

Figure 5. Mapping finger to tone.

Procedure

The study design is within-subject, and each subject had a session with each phrase. Audio playback occurred with both phrases, but only one phrase had tactile stimulation. At the start of each session, the subject was asked to first place their fingers on the keyboard (on the 5 keys) and listen to the first phrase while receiving the tactile cues from the glove. After this initial exposure, they were asked to play the phrase; performance was captured by the MIDI keyboard. Having had only one exposure, the subjects made many mistakes during this performance. The participants were then asked to perform a reading comprehension task consisting of SAT-level questions for 30 minutes while wearing the glove and listening to the phrase repeated in a loop.

The subjects were randomly divided into two groups, A and B. Group A received synchronized tactile stimulation for the session with phrase A, and group B received synchronized tactile stimulation for the session with phrase B. After 30 minutes, the subjects were asked to play the phrase again without any assistance, and their performance was captured. Each subject then repeated this process for the remaining song. To control for learning effects, we randomly divided each group into two subgroups, 1 and 2. Subgroup 1 learned their tactile phrase first, while subgroup 2 learned the tactile phrase second. The phrases were also randomly assigned. In sum, the study followed a randomized 2x2 Latin square design balanced for song phrase and tactile or non-tactile song.

During the 30 minutes of reading comprehension, only the tactile phrase would provide synchronized tactile cues via the glove. The reading comprehension questions were PSAT and SAT questions obtained from "testprepreview.com" and "majortests.com". There were 71 questions in total, and their order was randomized for each subject. The most number of questions answered by a subject after both 30-minute sessions was 64. The subjects were asked to proceed through the questions at their own pace, and an analysis of reading comprehension results was performed to compare the number of questions answered for the tactile and non-tactile sessions. The following is a sample question from the set:

Americans have always been interested in their Presidents' wives. Many First Ladies have been remembered because of the ways they have influenced their husbands. Other First Ladies have made the history books on their own. At least two First Ladies, Bess Truman and Lady Bird Johnson, made it their business to send signals during their husbands' speeches. When Lady Bird Johnson thought her husband was talking too long, she wrote a note and sent it up to the platform. It read, "It's time to stop!" And he did. Once Bess Truman didn't like what her husband was saying on television, so she phoned him and said, "If you can't talk more politely than that in public, you come right home."
. . .

What is the main idea of this passage?

A The Humanitarian work of the First Ladies is critical in American government.

B Dolly Madison was the most influential president's wife.

C Eleanor Roosevelt transformed the First Lady image.

D The First Ladies are important in American culture.

E The First Ladies are key supporters of the Presidents.

After each session, the subjects were asked to play the phrase for that session, and the performances were recorded. Analysis of the performances is described in the next section.

Analysis and Results

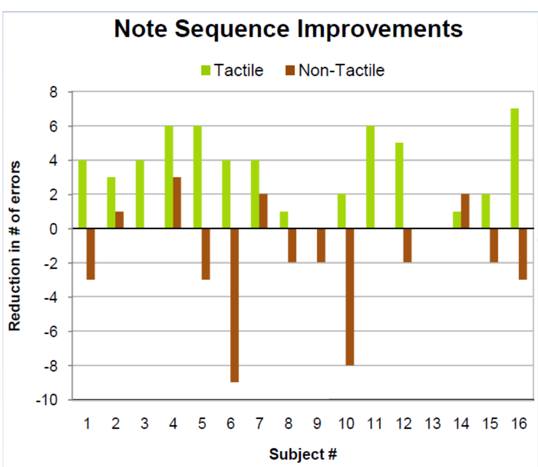

Figure 6. Improvement in performance of the note sequence (errors in initial performance - errors made after 30 minutes) with and without tactile stimulation of the fingers while performing a distractor task.

Each subject performed each musical phrase twice. The first is the initial-exposure performance where they had only heard and felt the song once. The second performance is after 30 minutes of reading comprehension during which they received passive tactile stimulation along with audio playback for the tactile phrase or audio playback alone for the non-tactile phrase. Figure 6 shows the improvement between these two performances. The error score is based on a Dynamic Time Warp (DTW) matching with the original correct phrase. Two DTW analyses were done, one for the note sequences (accounting only for pitch) and one for rhythm.

DTW Algorithm

Dynamic Time Warping is a dynamic programming algorithm for measuring similarity between two sequences which may vary in time or speed. In short, DTW is a method which finds an optimal match between two given sequences by minimizing the cost of mismatches. The two sequences are "warped" non-linearly during this matching process. The DTW function takes as input the two sequences and a set of costs and outputs the minimum cost (the error) required to match these sequences. The set of costs are:

1. cost of a match ($cost_m$)
2. cost of introducing a gap in the first sequence ($cost_{gap1}$)
3. cost of introducing a gap in the second sequence ($cost_{gap2}$).

Results of Note Sequence Analysis

The first analysis was performed solely on the notes, that is, whether the subjects pressed the right key sequence for the phrase, disregarding the rhythm. This analysis examines only note substitutions, insertions and deletions. Sequence 1 in this case was the original correct phrase and sequence 2 is the subject's performance as recorded by the MIDI keyboard. The DTW cost for a note substitution (mismatch), note insertion ($cost_{gap1}$), and note deletion ($cost_{gap2}$) were all treated equal and set to 1, making the metric equivalent to the ISO standard on speech recognition accuracy. For example, in

Original: C D E C G F D D **-** F E C
Perform.: C **E** E C **-** F D D C F E C

The top line is the original correct sequence and the bottom is the subject's performance. In this case, the total error is 3: there is a substitution (E), a deletion (missing G) causing a gap in the bottom line, and an insertion (extra C) which created a gap in the top line.

Table 2 shows the errors for the 16 subjects. Column 2 is which phrase was designated tactile for that subject. Column 3 is the "Error Initial" for the tactile song (i.e., the performance after the user initially heard and felt the phrase once). Column 4 is the "Error After" which is the number of errors in the performed note sequence after the subject heard and felt the phrase for 30 minutes while doing the reading comprehension distraction task. Column 5 is the improvement as determined by subtracting the number of mistakes made before exposure to MMT to those made after exposure. Columns 6-8 are the data for the non-tactile phrase, where the user only heard, but not felt, the phrase during the 30 minutes.

Subj #	Group	Error Initial (Tactile)	Error After (Tactile)	Improvement (Tactile)	Error Initial (Non-Tactile)	Error After (Non-Tactile)	Improvement (Non-Tactile)
1	B	4	0	4	5	8	-3
2	A	4	1	3	9	8	1
3	B	4	0	4	7	7	0
4	A	6	0	6	4	1	3
5	B	6	0	6	4	7	-3
6	A	4	0	4	6	15	-9
7	B	5	1	4	8	6	2
8	A	4	3	1	4	6	-2
9	A	5	5	0	4	6	-2
10	A	2	0	2	5	13	-8
11	B	6	0	6	5	5	0
12	A	5	0	5	5	7	-2
13	A	3	3	0	3	3	0
14	B	8	7	1	2	0	2
15	B	5	3	2	4	6	-2
16	B	7	0	7	4	7	-3

Table 2. Performance of both songs after 30 minutes of task activity.

Improvements in performance errors for note sequence

As shown in Figure 6, most tactile melody performances improved, while many of the non-tactile melody performances degraded. This result is expected because throughout the 30 minutes of no tactile reinforcement, the user usually begins to forget how to play the phrase as learned from the initial exposure.

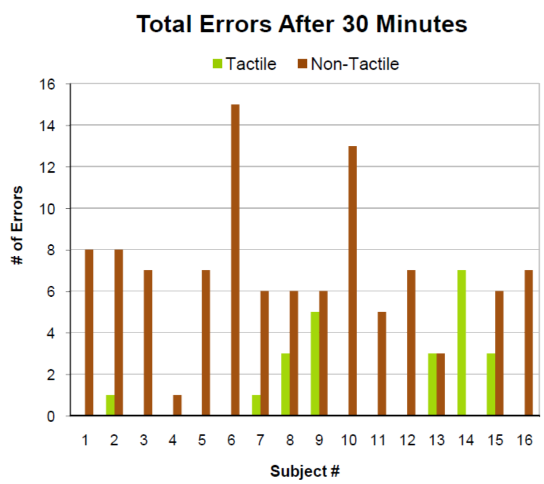

Figure 7. Errors in performance after 30 minutes (pitch).

As shown in Figure 7, the subjects made many more errors when there was no tactile reinforcement during the 30 minutes of reading comprehension. A two-tailed paired t-test comparing the improvements of the tactile and non-tactile melodies showed a p-value of 0.0001. The mean improvement of tactile group was 3.44 notes with a standard deviation (SD) of 2.25. The mean improvement of the non-tactile group was -1.63 with a SD of 3.30.

Analysis of Rhythm

Another aspect of playing a song correctly is the rhythm (i.e., the intervals between the notes). During the analysis of rhythm, note pitches were disregarded and only the note durations were input into the DTW algorithm. To account for rhythm, the set of costs are changed as follows:

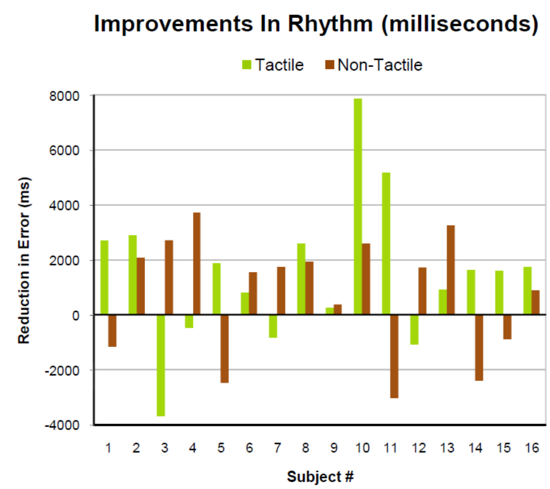

Figure 8. Improvements in rhythm (in milliseconds).

- Cost of matching A[i] with B[j] = ABS(duration of A[i] - duration of B[j]) where A and B are the two phrases, i and j are indices of the notes of these two phrases, and ABS is absolute value.
- Cost of a gap in A = duration of B[j]
- Cost of a gap in B = duration of A[i]

The durations are measured in milliseconds. The error values are the total cost (mismatched milliseconds). Figure 8 shows the improvement (error of initial performance minus error of performance after 30 minutes) for the tactile and non-tactile phrases.

A two-tailed paired t-test of the rhythm improvements showed a p-value of 0.437. The tactile phrase had a mean improvement of 1502 ms with a SD of 2640.83, and the non-tactile phrase had a mean improvement of 790.94 ms with a SD of 2153.03. While the mean improvement was higher for tactile, it was not significant due to the high variance. Upon reviewing the recordings, a possible reason for these results is the subject's philosophy in performing. When a subject did not know which keys to press, he may simply press random keys at the correct rhythm. But when a subject had an idea how to play, he/she would "stall" for a moment to remember the key sequence. In one example, a subject held a half-second note for roughly 4 seconds while trying to remember the next notes. The subject played the sequence correctly, but these "stalls" resulted in large errors in timing. Results may be different if subjects were asked to make rhythm a priority and not to hesitate even when the sequence was not recalled immediately.

Reading Comprehension Comparison

In order to determine whether the passive haptic learning results are an effect of subjects attending one condition more than the other, we examine how the subjects performed on their active task, the reading comprehension questions. A paired two-tailed t-test on the percentage of correct answers for the tactile ($mean_{tactile}$= 64.47%) and non-tactile sessions ($mean_{non-tactile}$ = 62.71%) showed no statistically significant result. The total number of questions answered also did not show statistical significance ($mean_{tactile}$=19.31, $mean_{non-tactile}$=19.63).

User Feedback

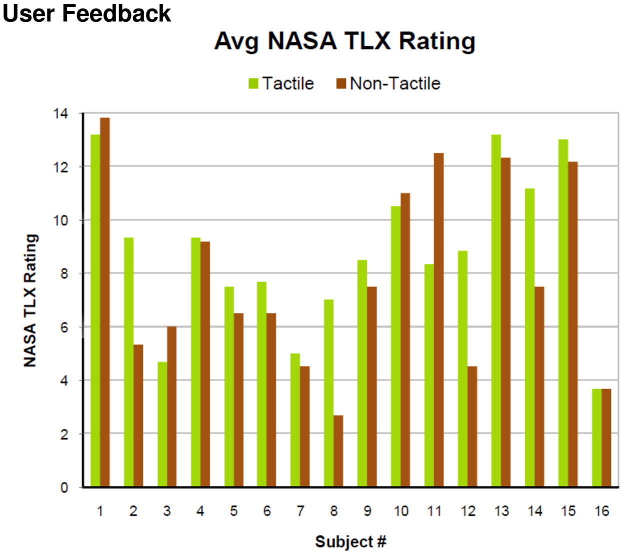

Figure 9. Average NASA TLX ratings.

In addition to the reading comprehension scores, we are interested in users' subjective impressions of the system. Does the tactile stimulation cause distraction or frustration during reading? To measure this possible effect, each subject was asked to complete a NASA Task Load Index survey after each 30-minute reading comprehension session. Figure 9 shows the average of all six variables for each subject. The variables are Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Each variable allowed the subject to check a rating from 1 to 21 with 1 being the least severe for that variable and 21 being the most. While some variables such as Physical Demand have little relevance to a reading comprehension task, we felt that Effort and Frustration variables should have high relevance. While the mean score for the Average, Effort and Frustration and was higher for the tactile sessions, a two-tailed paired t-test showed that the difference in scores between the tactile and non-tactile sessions were not statistically significant. The average TLX rating for $mean_{tactile}$ = 19.31 versus $mean_{non-tactile}$ = 19.63. For effort the $mean_{tactile}$ = 10.94 while $mean_{non-tactile}$ = 9.88. For frustration the $mean_{tactile}$ = 8.88 whereas $mean_{non-tactile}$ = 7.44. The other four variables, which were considered to be less relevant, also showed no statistically significant differences.

Passive Learning Insights

After the study, the subjects were asked to comment on their experiences during the 30-minute tactile sessions and provide their insight on how they were able to learn while doing the reading task. Some remarked that they found the reading very interesting and did not notice the vibrations at all. These subjects reported that the learning occurred entirely subconsciously. Other subjects remarked that they knew the vibrations were there in the background but did not shift their attention to them. However, these subjects remarked that during the reading, they "caught" tactile cues in moments of attention gaps, such as when switching between questions or passages. As described by Krugman above, passive learning is "caught rather than taught," and that seemed to have occurred in this study in a similar fashion. One subject expounded on this phenomenon by remarking that, in his experience, when one performs a lengthy daily task, the mind is rarely narrowly focused 100% from start to end. Rather, one's attention is often porous and allows for information to seep through when such information is provided in a pervasive, permeating manner. The last subject (subject #16) had a notably unique experience with the tactile session. This subject had very long fingers which caused the vibration motor to sit just beneath the middle knuckle of each finger. The subject remarked that though his attention was focused on the reading during the 30 minute session, he occasionally noticed that the vibrations caused his fingers to jolt in a manner similar to a knee-jerk reaction. He remarked that this reaction further strengthened the muscle memory of how to play the song. Thus, it appears that the position of the vibration motor on the finger may be more important than previously thought.

EXPERIMENT 2: COMPARING TIME FOR ACTIVE TRAINING VERSUS PASSIVE TRAINING

In the first experiment, the participants showed significant improvement in their ability to play a sequence of notes correctly with 30 minutes of practice. However, how much time would have been needed if the users simply focused on the task of learning? Perhaps one can predict the amount of time required to learn a pattern with passive training given the amount of time normally required to learn the pattern with active training.

Such knowledge would be of practical importance. If our eventual goal is to enable learning of longer songs, a reasonable approach would be for MMT to train users on the short phrases that compose the song individually. Thus, if MMT is worn for many hours during the day, it should transition to a new phrase when the current phrase has been learned. However, testing the user on a keyboard for each phrase throughout the day would be impractical. Instead, if we can predict the amount of time a given user typically requires to learn a short phrase by having him first learn a couple phrases actively, MMT could present successive phrases after appropriate time intervals of passive learning.

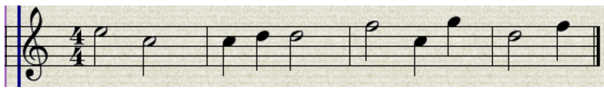

Figure 10. Example of a randomly generated sequence. These 10 note sequences consisted of quarter and half notes and the same five tones from the previous study.

Experiment 2 is a within-subjects study designed to compare active and passive training. It was performed with 10 users under controlled laboratory conditions and was divided into active and passive training sessions. A balanced design was employed to determine which condition the subjects experienced first. In the active part of the study, subjects learned a randomly generated 10-note sequence (composed from the same five tones as the previous study) by repeatedly attempting to reproduce the sequence. A MIDI piano keyboard would play the sequence and display the keys required by lighting them with LEDs hidden under each key. The subject would then attempt to repeat the sequence. This process would continue until the subject repeated the sequence correctly. Only the proper sequence of notes was required; rhythm was not considered.

During passive learning, a different random sequence was learned (see Figure 10 for an example). As with active learning, the piano would play the sequence, and the subject would try to repeat it. However, if the subject could not correctly repeat the sequence, they would spend 20 minutes on a distraction task before trying again. Subjects programmed, played video games, or performed office work during the 20 minutes, and the sequence was presented repeatedly by the MMT in both audio and tactile form. Since each attempt at reproducing the sequence is an example of active learning, one could argue that if the same number of attempts were necessary in the active and passive conditions, then very little learning was occurring in the passive condition.

During pilots of the study, subjects with a musical background seemed to have difficulty with the passive learning task. Thus, we decided to separate subjects into groups by their musical experience. Of the 10 subjects recruited, five had a musical background.

Hardware

A new, more robust MMT system was used for this experiment (see Figure 11). A flat ribbon cable containing the wires to the vibrators was carefully sewn to the outside of the glove, and the Bluetooth receiver, controller, and rechargeable Lithium polymer battery were mounted on the wrist in one box. The cable connecting the glove and the controller box was designed so that the connection would break away in case of snagging. The system was controlled via the Openmoko Neo Freerunner cellular phone running Linux, and the entire system had a battery life of approximately eight hours. While two sets of two gloves have been designed and tested, preparing for future studies, only the right hand glove was needed for this experiment.

Figure 11. Improved MMT system.

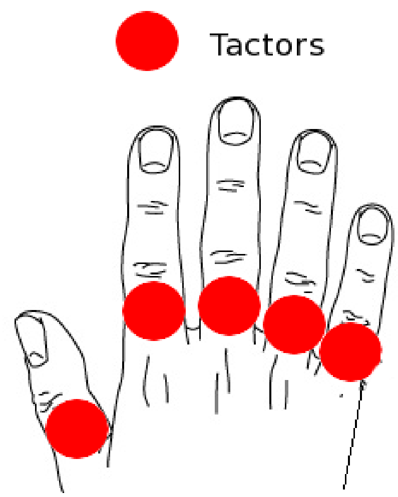

Figure 12. Mounting locations of the vibrators in the new MMT.

A significant difference between the gloves in the two experiments is that the vibrators in the second experiment were mounted closer to the subject's knuckles (see Figure 12). When a vibrator was activated, the whole finger felt the vibration, possibly due to a bone conduction effect. Several subjects said that the vibrations were too strong or felt they were mounted on the wrong place. Many of the participants said that it was difficult to distinguish between the fingers, especially between the ring and small finger. Upon more closely researching the anatomy of the hand, this observation makes sense. The parcini corpuscles that sense vibration in the hand are sparse in the ring and little fingers.

Data analysis

The subjects' performances were analyzed according the note accuracy and rhythm as described above. The two groups, "skilled" and "unskilled," were kept separate for analysis. Skilled users are experienced in music and mostly had played piano in the past. Unskilled users had no experience.

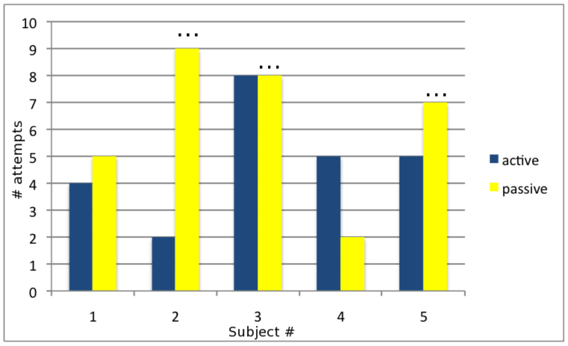

Figure 13. Attempts required to repeat the note sequence accurately for skilled subjects in the active and passive conditions. (...) indicates that the subjects quit the condition before being able to repeat the sequence.

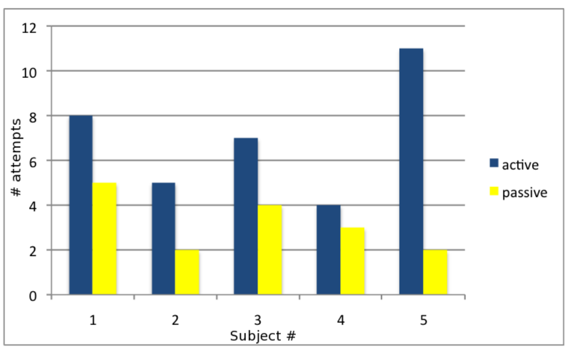

Figure 14. Attempts required to repeat the note sequence accurately for unskilled subjects in the active and passive conditions.

Figures 13 and 14 show the number of attempts needed by the skilled and unskilled subjects to repeat the note sequence. Note that over half the skilled subjects quit the passive condition before completing the task! However, all the unskilled subjects completed all tasks. The time between passive attempts was approximately 20 minutes. The time between active attempts was approximately 30 seconds. Unskilled subjects averaged 7 attempts for the active condition and 3 attempts for the passive session. The difference between conditions for the number of attempts was statistically significant ($p < 0.05$). Skilled subjects averaged 5 attempts in the active condition and over 6 attempts for the passive condition (note that most stopped before completion).

Comparing the time the subjects required to passively train to zero errors, the unskilled subjects needed significantly ($p<0.01$) less time than the skilled subjects for completion. The mean time the unskilled group needed is 5,842 seconds while the skilled group needed 12,952+ seconds. The time required for passive and active training for the unskilled subjects was correlated with $r=0.57$.

The rhythm score of the last iteration of each user was compared between groups, but no statistical significance was found. Again, in practicing music, most learners try to perform the note sequence correctly first and afterwards learn to play the rhythm correctly.

DISCUSSION

The results from the first experiment suggest that the subjects were learning the required sequence of finger motions during the 30-minute reading comprehension test when audio and tactile stimulation were employed and not when the audio alone was played. In addition, the tactile stimulation did not seem to add significantly to the participants' perceived workload. However, the subjects performed poorly on rhythm. This result may be due to a natural tendency for slowing performance in order to concentrate on performing the note sequence correctly.

Unintuitively, the second experiment showed that subjects with a musical background had difficulty in learning the note sequence in the passive condition. One possible explanation is that the songs were randomly generated and relatively amusical. Perhaps when the skilled subjects focused actively on learning, they could overcome their trained biases and learn the sequence; however, during the passive condition their previous experience overwhelmed the provided training. The unskilled subjects' ability to repeat the note sequence in far fewer sessions in the passive condition versus the active condition again showed the potential viability of Passive Haptic Learning. In addition, the correlation between time required to repeat the sequence in the active condition versus the time required in the passive condition suggests a potentially predictive relationship between active and passive training.

Design Implications of a Passive Haptic Device

Since sensory perception varies throughout the different parts of the hand, the location of vibration should be considered with care. For example, the 16th subject in the first study reported an involuntary twitch in response to the vibration motors resting just below his second knuckle. This location was unique due to his long fingers. He reported that the twitch was significant since it contributed to muscle memory. However, sensory acuity should be balanced with non-obtrusiveness. In our design, we considered placing the motors in the ventral (palm) side of the fingers where there is more sensitivity. However, this would fundamentally interfere with grip and hinder many activities.

Another consideration is comfort, which can be influenced by the material's weight , breathability, flexibility, and coarseness. Since passive devices in general need to be worn for long periods, comfort would be essential in its adoption. Participants' reactions to the comfort of the MMT glove were mixed. Some said that it was very comfortable while others said the material would need to be changed for long-term wear. In addition, some subjects felt that the vibrations were too strong and should be more muted if they were going to wear the system over and extended period of time.

A third consideration for the design of a passive tactile device is strap-time — the amount of time required to don and doff the device. At one point in our design, we considered using Velcro rings instead of a glove. While this design would be much more comfortable since the hands would not be covered, we found that its strap-time was too high. In that design, the user would wear a wristband which housed the microcontroller and then place each ring on individually and secure them. It would also be time-consuming to remove the rings one by one. This high strap-time led to a feeling of the device being "trapped" on the hand. From this experience, we believe that quick donning and removal is necessary for psychological comfort, which sometimes may outweigh the physical comfort.

FUTURE WORK

Furthering Ecological Validity

In the future, we plan to explore more complex piano songs for experiments with more ecological validity. The melodies in this study were created to be simple in the interest of experimental rigor. It is difficult to conjecture how well PHL will work with songs with more rhythmic and melodic complexities. We hypothesize that PHL exposure time would need to increase as a song's difficulty increases. However, as a user mentioned in the pilot test, certain notes and phrases absorbed by PHL may be able to provide hooks into memory, much like mnemonic devices, to aid in remembering other parts of the song. Much like how people can recover lost items by thinking about where they were last, PHL may facilitate recall by providing access to links in the chain of memory. However, this conjecture must of course be tested by experiments. We also plan to test MMT with other instruments such as saxophone, flute, recorder, etc. where the key-to-finger mappings are more 1-to-1. Given a smaller key-to-finger ratio than the piano, these instruments may lend themselves better to MMT. We would like to determine if users can learn new songs on these instruments in a passive setting without the initial exposure. We would also like to determine if a person can wear the MMT glove for a period throughout the day while doing their regular daily routines and be able to play entirely new songs at the end of the day.

Hand Rehabilitation

Another potential application for MMT is in the area of hand rehabilitation. MMT may provide an engaging and stimulating activity for exercising the hand. It has been documented that motivation is a prime factor in the recovery process [8]. Unfortunately, many traditional therapies involve monotonous repetitions of certain motions every day. For example, hand rehabilitation patients may be asked to touch their thumb to their fingers on the same hand or squeeze a ball for several hours a day. These routines are sometimes quickly abandoned. MMT can provide an engaging and motivating alternative or augmentation to such traditional therapies. It has been shown that playing instruments such as the keyboard can improve finger strength and dexterity as well as the feeling of mental well-being [16]. In this regard, MMT can stimulate patient's afferent nerves and help them exercise their hands in a fun way while teaching them a lifelong skill to prompt continued exercise. To explore this concept, we conducted a pilot study with two spinal-cord injury patients who have partially lost motor and sensory function in their hands and have plateaued in their recovery for over eight months. The study was performed in collaboration with the Shepherd Spinal Cord Rehabilitation Center. In the study, both participants were asked to learn beginner piano songs (e.g. "Jingle Bells", "Amazing Grace") for 30 minutes a session, 3 times a week for 4 weeks with MMT. During each session, the participants wore the glove and used auditory, visual and tactile cues to actively learn the songs. After the 4 week period, the subjects showed improvements in both motor and sensory function. Participants reported that the tactile modality of MMT encouraged them to actively engage their mind to focus on the hands' sensations, a factor which they felt contributed to their sensory improvement. One of the participants also reported more active use of his hand in other areas of his life (e.g. typing his own emails instead of dictating) after MMT training.

Aside from sensory function, MMT may also help improve motor function. It has been shown that stimulation of the afferent (sensory) nerves can increase flexibility and range of movement and decrease muscle spasticity [3]. Dr. Dimitrejevic writes that "diminished afferent input to the brain from the affected hand is a common deficit after stroke. Patients become less aware of their affected upper extremity because of sensory loss and partial paralysis. As a consequence, they use that extremity less and less, learning to use the unaffected arm in its place. Over time, disuse weakens muscles and most likely reduces the representation area of the affected part in the cortex" [3]. Doidge [4] discusses similar mechanisms for many different aspects of rehabilitation. MMT may be able to provide the tactile stimulation needed to diminish the extent of deficit from de-afferentiation of the hand.

CONCLUSION

We have presented two studies that suggest that Passive Haptic Learning can be used for learning to perform sequences of keypresses. Future work will examine whether the system can be extended to musical scores. Unintuitively, the system seems to work better for subjects without a musical background, which suggests a direction for further study. Finally, initial work suggests that the MMT system may be useful for hand rehabilitation, a direction we are currently pursuing.

ACKNOWLEDGEMENTS

The authors wish to thank Professors Mark Guzdial and Richard Catrambone for their user study suggestions and Dr. Debbie Backus and Ben Lippincott for their suggestion that MMT might be useful for hand rehabilitation and help in the rehabilitation pilot.

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