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Towards Passive Haptic Learning of Piano Songs

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***Abstract*— Passive Haptic Learning (PHL) enables users to acquire motor skills by receiving tactile stimulation while no perceived attention is given to learning. Initial work used gloves with embedded vibration motors to passively teach users how to play simple, one-handed, one-note-at-a-time piano melodies. In an effort to create a practical system for learning full piano pieces, we have developed a method of passively teaching two-handed chorded skills, initially focusing on Braille typing. Here, we extend this effort to piano and show that passive stimulation is more effective at teaching piano pieces when presented on both hands simultaneously as opposed to training the left hand and then the right, as is common in many active teaching methods. We also demonstrate that accompanying audio is not needed for passive learning of piano melodies, which allows mobile PHL gloves to be used in more everyday situations.**

I. Introduction

Passive Haptic Learning (PHL) is a phenomenon where users can learn motor skills through haptic stimulation, even though little to no attention is dedicated to learning. Stimulation is provided by a tactile interface, and users focus their attention on another task (like completing a standardized test or playing a video game) while they passively learn [10], [12]. Previous work in this area used gloves with embedded vibration motors to teach users how to play piano melodies or how to type Braille [10], [21]. Given that the effort on Braille demonstrated that PHL can be applied to two-handed chorded typing, perhaps the same techniques can be applied to synchronized, two-handed chorded music? In addition, previous passive piano learning was coupled with audio of the song, which is annoying if the user is doing a primary task which also requires audio. Is audio necessary or is tactile stimulation alone sufficient for passively teaching motor skills? Here we:

- Demonstrate Passive Haptic Learning/Rehearsal without the need for accompanying audio
- Explore Passive Haptic Learning of chorded, two-handed piano music
- Present and contrast two successful methods of teaching complex piano melodies via haptics

II. BACKGROUND

Learning is not always an active process; it can sometimes be passive. Passive learning 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" [13]. Subjects who live in a media rich environment and are passively exposed to political information are 40% more likely to acquire the information than subjects living in a media poor environment [25]. A media-rich environment need not be limited to audio and visual stimulation though.

It has been shown that a multi-modal combination of audio and haptic cues gives users a richer understanding of musical structure and improves performance on music pieces [9], [15], and in a series of experiments, we showed that manual skills can be learned or reinforced passively while the user is engaged in other tasks using tactile stimulation [10], [12], [21]. Other researchers have examined haptic feedback for motor skill training [2], [7], [17], [19], [22] and memory [11], [23]; however, this work focuses on kinesthetic feedback and active participation by the user. Here we focus on passive tactile learning.

Previous research on Passive Haptic Learning concentrated on simple, one-handed, one-note-at-a-time piano melodies. Wearers of gloves with a tactor at the base of each finger could learn about 45 notes, on average, of a song like "Amazing Grace" in a learning period of 30 minutes [10]. In these experiments, performance on the primary "distraction" task (mathematical and reading comprehension exams, scavenger hunts, memory games, etc.) is not degraded while the participants receive passive stimulation [12]. However, when one of the authors used the system to train himself to play a new song while presenting a talk on Passive Haptic Learning at a conference, the audio proved highly distracting, leading to the experiment that attempts PHL without audio below.

Fig. 1. A PHL glove used in teaching piano melodies.

Expanding on research in passive piano learning, we endeavored to examine a new application of Passive Haptic Learning: Braille typing [21]. Braille typing is a complex skill to teach passively as it is a discrete system yielding language. It uses both hands and is "chorded" (requiring multiple keystrokes to yield just one character) with each of the index, middle, and ring fingers of each hand dedicated to its own key. In preliminary studies, we discovered that our participants could not sense simultaneous stimulation of multiple fingers with accuracy. A key insight was to

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sequentially stimulate each finger in a chord, with temporal offsets between chords. After this change, results were highly promising. Users demonstrated significantly reduced error typing a phrase in Braille after receiving passive instruction (32.85% average decline in error) versus control (2.73% increase in error), and in a follow-up full study we taught the full Braille alphabet in less than four hours [21]. Figure 2 illustrates some results. Given this method of training two-handed chords, we decided to pursue a more ecologically valid goal of passively teaching piano pieces that require complex chorded manipulation using both hands.

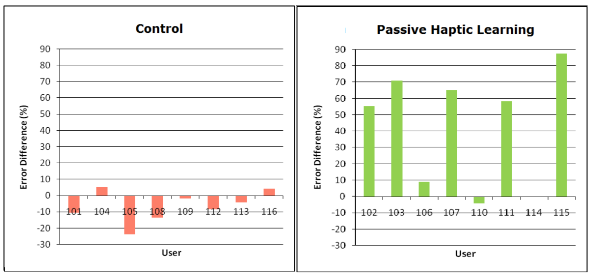

Fig. 2. User typing performance improvement on one of the phrases in Braille after Passive Haptic Learning or the control condition.

III. Apparatus

For both studies below, we use a system consisting of a glove or a pair of gloves outfitted with a vibration motor on the back of each finger near the knuckle (ventral side of the hand). In addition, the hardware includes a microcontroller that controls and drives the glove(s).

Each glove contains five vibration motors (one per finger). The vibration motors are Precision Microdrives Eccentric Rotating Mass (ERM) tactors (part #310-113) in the coin form factor. 3.3V DC provides results in the peak recommended vibration strength (1.38 G) and 220Hz vibration frequency (increases proportionally with applied voltage). All motors are held flush with the fingers by the fabric making up the gloves. The gloves are fingerless to provide optimal fit for varying hand size.

Both experiments tested users' performance on a Casio piano keyboard with keys that light under program control. The piano was connected to a PC using a USB cable which enabled communication and recording of what is played into MIDI format.

IV. Accompanying Audio

Is audio stimulation needed for successful learning, or is tactile stimulation enough to passively practice a motor skill? We hypothesize that both conditions present similar results.

A. Initial Study

In an initial study, we examine two conditions of PHL's effect on a person's ability to retain what is learned during an active practice session of piano. In essence, we are using our gloves for Passive Haptic Rehearsal to prevent forgetting of a piano melody. The two conditions are: using only vibration versus PHL using the vibration and audio. Each subject is tested under both conditions at different times, using one of two chosen song phrases each time. This within-subjects experiment uses 12 participants and is randomized and counterbalanced for phrase and condition.

The 45-note song phrases were selected from "Jingle Bells" and "Amazing Grace" arranged to be performed using only the right hand (one key at a time). These phrases were broken into four sections and, we begin the study by allowing users to practice each of these sections by watching the phrase on the keyboard as it lights each key while the song plays. Users rehearse each section, followed by the full phrase, until they reach zero error on the note sequence. Upon learning of the song, users spend a forgetting period of 30 minutes taking a GRE reading comprehension section while experiencing either the vibration or the audio+vibration stimulus from the system. This Passive Haptic Rehearsal variant on PHL also illustrates passive "practice" of a motor skill; but here, we test non-novice users (as opposed to those never having played the piece) – especially useful for skills requiring maintenance (such as music or stenotype [14]). During the vibration-only condition, participants feel the fingers used to play the song "tapped" by the glove in the proper sequence and timing. Participants experiencing the audio+vibration condition "feel" the song being played through the haptics and also hear the song playing from the computer speakers. At the end of the GRE distraction task the participant removes the glove and is given three attempts to play the song phrase without any cues.

Each participant's performances are recorded in MIDI format and evaluated using a Dynamic Time Warping (DTW) algorithm, to account for errors of substitution, insertion, and deletion [10]. DTW findings the optimal match between two sequences, minimizing the costs associated with various types of error. This method is similar to the ISO standard for speech recognition accuracy. Using a paired t-test, we compared the errors made in the vibration-only condition with those in the audio+vibration condition. There was no significant difference between the conditions for any of the three attempts ($ATT1mean_{vib}$ = 2.08 vs. $ATT1mean_{aud+vib}$ = 2.25, p = 0.74), ($ATT2mean_{vib}$ = 1.08 vs. $ATT2mean_{aud+vib}$ = 0.92, p = 0.76), ($ATT3mean_{vib}$ = 0.42 vs. $ATT3mean_{aud+vib}$ = 0.92, p = 0.11). We also compared the average of the three attempts ($AttAVGmean_{vib}$ = 1.19 vs. $AttAVGmean_{aud+vib}$ = 1.36, p = 0.60), and finally the best of the three post attempts: ($BESTmean_{vib}$ = 0.25 vs. $BESTmean_{aud+vib}$ = 0.25, p = 1.00). We found that there was no statistically significant difference in any of these cases (see Figure 3). We also evaluated the participants' GRE scores. Using the 2-tailed, paired t-test, we found no meaningful difference between the values ($GREmean_{vib}$=22.58 vs. $GREmean_{aud+vib}$=22.67, p = 0.92).

B. Four Condition Study

To elucidate these results, we next contrast four conditions in a follow-up study: control (no intervention), audio (music) only, vibration only, and audio+vibration. This within-subjects study, containing 24 participants with no piano experience, follows a similar structure to that of the first.

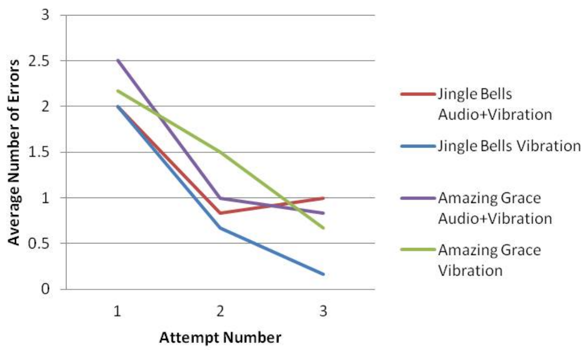

Fig. 3. Results for the initial study of Passive Haptic Learning with of without accompanying music. Errors after the forgetting period are shown for each attempt under each condition (separated by song).

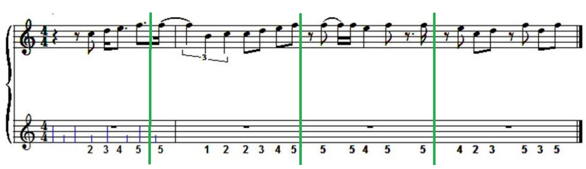

Fig. 4. One of the four generated song phrases from the four condition study. Lines show subsections used in active practice.

In this study, users come for four sessions and encounter a different condition and musical phrase (one of four) each visit. We counterbalance for phrase and condition. We aim to contrast these conditions, furthering our determination of what stimuli contribute to Passive Haptic Learning. We hypothesize that the three non-control conditions (audio-only, vibration-only, audio+vibration) will result in lower error scores than the control condition. We expect the tactile conditions of vibration-only and audio+vibration will show significant improvements in error scores over just the audio condition or the control condition.

In order to avoid variance due to song selection, we use four newly generated music phrases. To create these songs, we used ”Wolfram Tones” – a software that takes user constraints and generates ”musical” passages. We constrained these songs to match the five fingers of the right hand to five keys on the piano, with no simultaneous notes (chords), and to have 22 notes (see Figure 4).

The study followed the same structure as the first:

1) Practice parts of the phrase, and eventually the whole phrase (guided by the light-up keys) *
2) Take the GRE test while receiving one of the four conditions (quantitative section, 30 min.)
3) Three attempts to perform the music phrase

A change was made (*) from the original study: users were not permitted to practice until perfect to avoid a ceiling effect on shorter phrases. They were given one try at each subsection, five tries with two subsections together, and 10 attempts at the full phrase. At the end of a session participants also completed the NASA TLX assessment, evaluating their perceived workload during the 30 minute GRE period while experiencing one of the four conditions.

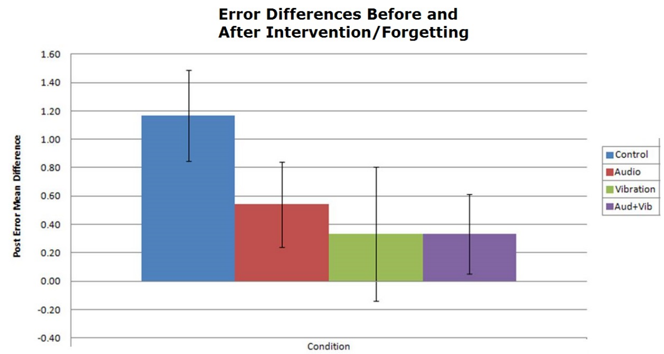

Fig. 5. Mean error difference (error increase from before the forgetting period) by condition.

C. Results

Recorded performances were analyzed for error rates using a Dynamic Time Warp. The best of the three post attempts was compared with the last attempt at the entire phrase during the practice session – yielding error difference scores before and after the GRE distraction ”forgetting” period. In a comparison with the control group performance: audio+vibration was found to demonstrate a statistically significant improvement in error scores versus the control case, with a p-value of 0.02 (one-tailed paired t-test) and an effect size of 0.16 (large effect). Vibration alone was also found to have an effect when compared to control with a p-value of 0.05 (one-tailed paired t-test) and effect size of 0.11 (moderate effect); while the audio alone condition showed no significant difference from control with a p-value of 0.08 (one-tailed paired t-test).

As expected, the control condition resulted in the highest increase in the number of errors with an average increase in errors of 1.17. The audio-only condition showed an average increase in 0.54 errors, while both the audio+vibration and the vibration-only conditions averaged an increase in errors of 0.33 over the 24 participants. No significant difference was found in the GRE scores for any condition, revealing that the participants appeared to have given a similar amount of attention to the GRE test regardless of the condition applied. When examining perceived “load” (NASA TLX) we looked particularly at the two cases that most point toward distraction: Effort and Frustration. We found no significant differences between the averages of the conditions for Effort; while participants assigned a higher rating for Frustration when comparing the audio+vibration condition (average rating of 11.25) to control (average rating of 8.5) resulting in a two-tail paired t-test of p = 0.01.

D. Discussion

This study revealed that audio alone, vibration alone, and audio+vibration all result in an overall lower error score than the control case. This result suggests that such interventions are worthwhile for learning and retention. While the audio+vibration case did achieve statistical significance for error differences, this condition also had a higher frustration rating when compared to the control condition. Vibration-only achieved marginal significance for the error difference (due to its higher variation in results – the average error increase was the same as audio+vibration), but had lower NASA TLX scores, suggesting less distraction. To design a tactile teaching system for use in daily life, we must consider not only the glove's effectiveness, but also its potential to cause unwanted distraction, rendering it undesirable for long-term wear. The study's results justify the use of vibration alone instead of having to incorporate audio to aid in learning and retention, and subsequent pilot studies have demonstrated that haptics alone is been sufficient for passive learning, even with no initial practice.

V. Teaching Two-Handed Pieces

With the objective of passively teaching complex piano pieces, we conduct a study examining this task's feasibility and teaching structure. The study is structured in a similar manner to the feasibility study conducted for PHL of Braille: teach users two "phrases" under different conditions and examine learning. This study aims to demonstrate both internal validity of passively teaching advanced, two-limb music containing chords and to examine what method is best for learners (passively learning one hand at a time, or both together).

Braille is inherently chorded and requires the synchronized use of both hands to produce most letters. However, there exists a dichotomy in the musical methodology regarding how to learn two-handed pieces. Typically, when learning a piece of music that uses both hands, piano students learn to play one hand and then the other before playing both parts together. However, music research literature views learning both hands together from the start to be more advantageous [5], [6], [20]. Even so, in teaching and practice, it is viewed as largely too challenging to learn both hands at once, a stance with which research concurs [5], [6], [8], [20], [24]. Difficulty is posed by having to divide attentional resources between both limbs when learning a dexterity skill ("especially when playing a more complicated piece of music") [5], [8], [24]. These views suggest that learning one hand at a time may help make learning more palatable. In addition, original piano PHL work efficiently taught a lengthy sequence of notes to one hand, whereas our two-handed Braille work taught discreet letters, not an entire sequence. Teaching advanced piano blends challenges from both of these tasks. We hypothesize that passive teaching of both hands together is possible and thus allows for a more rapid reduction of errors in playing the piece as compared to learning one hand at a time.

A. Study

We investigated these teaching structures, as well as the potential for teaching two-limb, chorded music sequences passively, with a within-subjects user design containing eight participants. Each user attended two sessions – during each they passively learn one of two music phrases under a different condition each time. The study is counterbalanced for phrase and condition. The conditions examined here concern how the haptic gloves passively teach participants:

1) "LR" (left-right) condition: users learn the left hand's part followed by the right hand (as piano students typically learn)
2) "Sync" condition: users learn both hands together (as they would perform the song)

We selected the phrases from Mozart's "Turkish March" and Vivaldi's "The Four Seasons, 2ed movement: Spring." These phrases were chosen to contain chords over both hands as well as dissimilar parts for both the left and the right hand. In our past studies, we found Passive Haptic Learning is best presented in sets of 10-17 stimuli to be learned at a time, so we split each session into two learning periods (see Figure 6). During these periods users either learn the left hand portion followed by the right hand part, or, to keep session structure parallel and stimuli set lengths reasonable, they learn the first half of the phrase (both hands together) then the second half of the phrase. In the LR condition, we teach the left hand first because the left hand typically carries the more simple part (non-melody) of the piece.

Fig. 6. One music phrase used in the study (from 'Turkish March'). Divisions show what parts were learned during what condition's first and second learning period (Sync. (Parts 1 then 2) or L then R).

We recruited participants with no knowledge of piano and establish this fact using a pre-test at the start of each session. Their performance here acts as a baseline for comparison with a test given after they receive Passive Haptic Learning. For the pretest, we show users the music phrase being "played" on the lit keys of the piano keyboard (the phrases are programmed into the keyboard by us). We then tell them where to place their hands and ask them to play what they know. They are given one try at playing the phrase during the pre-test.

After the pre-test, users spend a learning period of 20 minutes receiving haptic stimuli while focusing their attention on an online game. During this time, participants wear the gloves and feel vibrations on their fingers associated with the music (see the Passive Haptic Learning Stimuli section below) for the part of the song they are learning. Participants are told to not pay attention to the stimuli and to only focus on getting a high score at the game. This game (distraction task) was previously selected for sensitivity as a distraction metric (see Seim *et al.* for more details of the game [21]).

After the first learning period, users are tested on their performance of the part of the song they learned passively. Users are allowed three attempts at playing the part. Before the first attempt, administrators play the song's audio, and before the last two attempts users are shown the piece "played" on the lighted keys. This structure illustrates what was initially passively learned and facilitates clarification of reaches/#'s during the piece. Users then enter the second learning period (with a new part of the song), structured identically to the first. After the second learning period and test, users are given a full test where they are asked to play the entire phrase (either by playing the left and right parts together, or the first part followed by the second part). They are shown the phrase "played" on the lit keyboard before each of three given attempts.

1) Passive Haptic Learning Stimuli: The fingers required to play each tone in the music are "tapped" using the vibration motors in the gloves. These haptic stimuli are synchronized with the tones of the music. Additionally this structure provides chord parsing information and action feedback: sequences yielding chords are separated by tones while keeping stimuli temporally tight, and users may have understanding of the tones to be expected when they "type" on the piano keyboard. Each tone of the song (or song part) is played into the participant's earbuds, and the finger or fingers required to play this tone are then stimulated sequentially. This process is followed by the next tone and stimuli until the end of the song (part), after which the system waits 20 seconds and repeats.

B. Results

Performance data was captured in MIDI format which represents what notes are played and on/off times. This data was then translated into ASCII for easier visual perusal and rapid, automated processing. A Dynamic Time Warping algorithm was used to analyze the distance between the sequences produced when testing users and the correct sequence of notes in each musical phrase. In the algorithm, each chord the user had played was either found to be entirely correct (a match) or was labeled incorrect (insertion, deletion, or substitution). For example, when looking for the chord '62-70-72' (three simultaneous keys) only an exact match would contribute no increase in distance (error); '62-70' would be counted as entirely incorrect. This distance measure is then divided by the max length of the phrase or input to yield %error, similar to the metric in text entry [16].

To examine the feasibility of passively teaching a sequence of two-handed key sets via haptics, without the active attention of the learner, we examine differences in performance error between the pretest and the average of the full post tests. In both conditions, LR and Sync, as well as overall, users demonstrated reduced error after receiving Passive Haptic Learning. Paired t-tests reveal that error differences between pretest and full tests (LR: M=33.60%, SE=0.0531; Sync: M=49.55%, SE=0.0547; All: M=41.58%, SE=0.0560) are significant (LR: $t(7) = 4.47$, $p < 0.0015$; Sync: $t(7) = 6.41$, $p < 0.00019$; All: $t(15) = 7.42$, $p < 2E\text{-}06$).

A "content sensitive" Dynamic Time Warp distance measure was also devised for better analysis of correct song content in which chorded inputs may be recognized as fractionally (rather than entirely) correct. This measure was developed to be more sensitive to learning differences, in case users did not learn or perform note groups (chords) correctly. Though non-typical in applications like text entry, where a similar Mean String Distance (MSD) measure is used to examine only whether a letter is entirely correct, applications similar to this one, where learning, dexterity, and performance are evaluated, may benefit from such a metric. Already, the standard DTW measure showed learning in our testing; this secondary measure is simply for additional insight. It too reflected a significant effect on error reduction between pretest (LR: M=82.76%, SE=0.0359; Sync: M=78.02%, SE=0.0412; All: M=80.39%, SE=0.0267) and full tests (LR: M=37.61%, SE=0.0398; Sync: M=27.40%, SE=0.0524; All: M=32.51%, SE=0.0331) when compared with a paired t-test (LR: $t(7) = 6.13$, $p < 0.0003$; Sync: $t(7) = 6.93$, $p < 0.0002$; All: $t(15) = 9.46$, $p < 1E\text{-}07$).

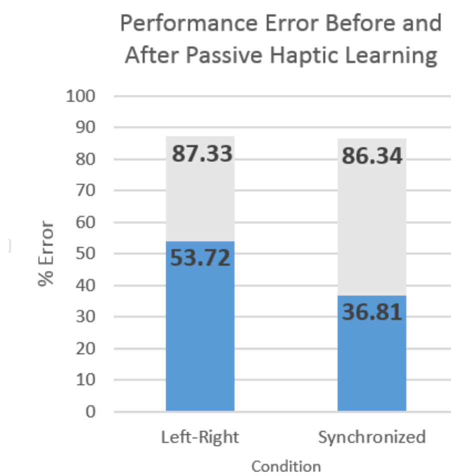

Fig. 7. Performance error by condition. Before PHL (gray) reflects pretest performance, and after PHL (blue) reflects average full post test performance (using original DTW).

Teaching conditions (LR or Sync) were compared for effectiveness. When users were given Passive Haptic Learning in the "Sync" structure, they presented both better ultimate performance and improvement from the pretest. Ultimate performance (lowest error in best full post test score) was examined for differences between conditions (LR: M=44.22%, SE=0.0562; Sync: M=23.12%, SE=0.0690) and compared with a paired t-test which suggests the differences are significant ($t(7) = 1.98$, $p=0.0443$). Improvement (error difference between the pretest and the average test performance) was also compared (LR: M=33.60%, SE=0.0531; Sync: M=49.55%, SE=0.0547) and significant differences were again found with a paired t-test ($t(7) = -2.19$, $p = 0.0322$). See Figure 6.

Content-sensitive DTW reflected closer performance on the full test between conditions which illustrates an observed performance behavior difference: users who were in the LR condition learned and played the notes for each hand, but failed to synchronize them into the correct chord arrangements for the piece when tested. This partially-present content was reflected in lowered error rates for this group when using the content-sensitive metric versus the original all-or-nothing DTW measure. Further examination of performance improvements demonstrated no ordering effect or significant difference in errors by song (which would reflect a potential difference in song difficulty). Comparison of performance on the distraction task (online memory game) showed no significant difference ($t(7) = 0.554$, $p = 0.300$).

C. Discussion

These results suggest complex piano pieces may be taught passively. Passively learning each part of the piece across both hands at once is possible and yields the best results. This result is consistent with research that suggests, if possible, it is best to learn both hands together [5], [6], [20]. Perhaps active learners can overcome their initial struggles with practicing with both hands simultaneously by first using Passive Haptic Learning! More generally, these results suggest the use of Passive Haptic Learning of synchronized, multi-limb skills for other instruments and other domains.

All users correctly played the notes of a chord together (when they were taught them together by the haptic interface – i.e., in the Sync condition) despite each stimuli being presented sequentially (slight staggered in time for perception). Before Passive Learning, users are told that each tone they hear is followed by stimulation on the finger or fingers to press that make that tone. With only this instruction, the interface successfully, passively enabled users to parse the stimuli and seamlessly self-synchronize.

VI. Future Work

Passive Haptic Learning has only begun to be explored. Questions remain ranging from: "What else can be taught passively via haptics?" to "What are the limits of PHL?" This work suggests a new direction in haptics research and deeper investigation into Passive Haptic Learning.

VII. CONCLUSION

We present the results from two investigations into Passive Haptic Learning. In the first, we find that passive vibration stimulus presents comparable, beneficial performance results to passive vibration+accompanying music. This result allows for development of haptic-only teaching systems which would be more practical for daily use. In the second study, we demonstrate successful, significant results teaching complex (two-handed, chorded) piano melodies to novices, using only Passive Haptic Learning. This work also established that users may learn to play both left and right hand's tunes at once – enabling a more rapid reduction of error using only the haptic glove system.

VIII. ACKNOWLEDGMENTS

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