Haptic Tutor - A haptics-based music education tool for beginners

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In this paper we introduce Haptic Tutor, a wearable haptic system for triggering vibrations on limbs of a student drummer aimed to help develop multi-limb independence. The system uses portable, wireless vibrotactile devices to display haptic information on drummers' limbs. To asses the usefulness of the system, we analyse response time differences between stimuli and motor action (drum stroke). Our hypotheses are that the use of haptic stimuli will improve the temporal characteristics of performances, but also that the type of haptic stimuli will have an influence on performance results. To validate these hypotheses we conducted two experiments. The first one with 30 participants randomly distributed in three groups, each group performing simple drumming lessons involving both hands under a given condition (no haptics, haptic pulse and haptic ramp). Results show clear improvement in strike accuracy for both haptic conditions, most clearly in the haptic ramp condition. Using these results, a second experiment was carried out in which 16 other participants were randomly divided into two groups (no haptics and haptic ramp conditions) and asked to perform a more complex lesson, this time involving three limbs (two arms and right foot). Results of both experiments show clear improvement on strike accuracy (reduced asynchrony), but a less important difference on strike precision (inter-onset-interval deviation) for the haptic condition. We finally report on participants subjective comments, discussing the limitations of the current prototype.

Background and motivation

Learning and playing a musical instrument requires various sensory modalities coupled with fine motor skills which require a great amount of time and effort to acquire. Since drum set beats/rhythms are a combination of multiple rhythmic voices (layers), multiple limbs typically play different rhythms at the same time. Achieving motor-limb independence to perform such coordinated movements is one of the biggest challenges for a drum set beginner. Novice players make various errors in the execution because they lack a well-established motor program for drumming action. [21]. Showing a demonstration of the desired playing method is the traditional way of transferring the interpretation-to-action model of the instructor to the learners. To get the same results during self-practice without instructors, other means such as ours can be very helpful to present demonstrations of the desired playing method. This practice will not only accommodate the preferred learning method of the beginner, it will also be a new tool for the education support of children with disabilities [4].

Humans tend to look for periodicities, in that we have a tendency to pay attention to periodic phenomena in the environment and imitate the perceived periodicities through bodily motions. This is true for all our sensory modalities; visual, aural as well as haptic [7]. Building on these basic phenomenon, in this research we wish to investigate if haptics can be used to develop more elaborate skills in reproducing rhythms. Previous research discusses about music educators observing students finding it difficult to develop multi-limb coordination from simply hearing, following written music or observing a music teacher [18].

Playing a drum beat involves a sequence of fast coordinated discrete movements of multiple limbs [20]. Drum beats form the rhythmic foundation (or 'groove') of music through the repetitive and rhythmic presentation of percussion sound patterns. Playing the drum beats correctly and fluently is vital to good drumming, so the learning of drum beats is the main content of drum lessons for novice drummers.

Sensory motor contingency theory [24], suggests that in order to organize and respond to sensory input in a certain domain, a learner's motor actions should be able to produce or affect relationships in the domain being sensed. When the input (sensory) and output (motor) domains do not match, the learner finds it hard to develop competency. In traditional drum learning, the stimuli is usually visual or aural, while the output domain is haptic. Another concept that drives this research is entrainment; multiple physically connected rhythmic processes interact with each other to eventually lock in to common phase or periodicity [7].

A further motivation for using haptics is linked to the strengths and weaknesses of different sensory modalities. The four processing stages of a stimulus-response task are stimulus detection (sensory phase), stimulus identification and decision (cognitive phase) followed by action (motor phase) [20]. Past research has shown that response time of tactile stimuli is 28% and 34% shorter than that of auditory and visual stimuli, and the response time of auditory is 5% shorter than that of visual stimuli [22].

Related Work

Several works on the use of haptics for communicating different kinds of musical information have been proposed, for example for notifications [23], posture improvement [11], tempo synchronization among musicians [2, 12], tapping synchronization to auditory rhythms [5, 17] and guidance/augmentation in musical practice [19, 15, 1]. There is less research on the use of haptics for communicating accurate temporal patterns aimed at developing multi-limb coordination in the context of drum learning. Lee et al. [20] designed a vibrotactile guidance system in which striking position is instructed by the body site stimulated by vibrotactile stimuli.The dense tactor placement (9 vibrotactile actuators) all over the body increased identification and detection time, though the accuracy of guidance was not significantly affected by body site or stimulus strength. Holland et al. [15, 3] explored haptic-based music learning by presenting short vibrotactile stimuli to the wrists and ankles of drum learners to guide several drum rhythms. The subjective evaluation

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and results indicate that beginning drummers are able to learn intricate drum patterns from the haptic stimuli alone, although haptic plus audio was the mode of presentation preferred by subjects. Interestingly, it was stated that vibrotactile cues were often unperceived by the learner due the impact that occurred at drum strikes. The work of Ignoto et al. [16] proposes that, in the context of haptic-based music conducting, one gets a better sense of when the next beat occurs when there is a ramp-up vibration to the maximum peak (at the stroke). In our research we apply this concept of ramped-up pre-vibration stimuli to the context of drum learning.

The Haptic Tutor aims to address the theories discussed above: considering the fact that the input (sensory) and output (motor) domains are both haptic, the periodic vibrations promote entrainment leading to drum learners developing skills in reproducing polyphonic rhythms. We aim to objectively and subjectively characterize improvement of timing accuracy and precision of the polyphonic rhythms learned and reproduced by the participants when using haptics. Finally, we wish to test if the characteristics of the haptic signal, focusing on having pre-vibrations, help to better anticipate beats, considering delays between the stimulus detection identification and motor movement in a stimulus-response task of following vibrotactile and audio/visual cues to produce multi-limb rhythms.

System design

In this section, we present a brief overview of vibractile displays followed by details of the haptic technology that is used in this research.

Vibrotactile Feedback

Our system uses vibrotactile displays to produce vibrations on the individual limbs of the drummer. Vibrotactile feedback consists of using vibrations as a means of transmitting information through the sense of touch. Devices called vibrotactile displays are used in transmitting information via vibrations [6]. Such displays can be used to transmit haptic effects or simulations with a wide variety of actuators, such as ERM motors or voice coil actuators.

The Vibropixels

The Vibropixels (Figure 1), developed at the Input Devices and Music Interaction Laboratory at McGill University, is a re-configurable and scalable wearable vibrotactile display system [14].

Figure 1: Vibropixels

A transmitter connected to a PC wirelessly sends control messages, generated by an interactive software (Max/MSP), to one or many different Vibropixels in the network; the Vibropixels are individually or group addressable. The parameters of the control message represent an envelope for the vibrotactile pulse and the receiving Vibropixel outputs the corresponding envelope. Two motors, a coin cell and a pager motor, are available and individually controlled allowing for different textures of haptic pulses to be generated. The modular design of the Vibropixels allows them to be reconfigured for use in a wide range of applications. For these reasons, the Vibropixels were chosen as the platform for developing the Haptic Tutor. Though commercial solutions for vibrotactile metronomes, such as the Soundbrenner[1] are also available, they output only discrete pulses. As our use case requires custom made pulses with ramp-ups for one of the conditions in the experiment, such solutions were not adapted to our needs.

Hardware configuration

Figure 2 provides a system overview of the hardware configuration of a single Vibropixel. The Vibropixels provide a combination of a coin-type and a cylindrical type ERM actuator, allowing for a wide combination of vibrations. Both motors are driven at a constant 3.3 V by an A3910 dual half bridge actuator driver, which provides two output channels with a combined maximum of 500 mA current. A rechargeable and replaceable AAA-size lithium-ion battery can drive the Vibropixel over 12-hour lifespans. The wireless transceiver module used is an nRF24L01 (2.4GHz) is low-power and is able to implement a network topology which can accommodate large numbers of transceivers. A commercially available radio module with an external SMA antenna and an additional RF amplification stage provided a stated +20dB boost to transmission power; this enabled stronger communication links and less packet loses in conditions when laptop and the haptic transmitter had to be placed relatively far from the student drummer.

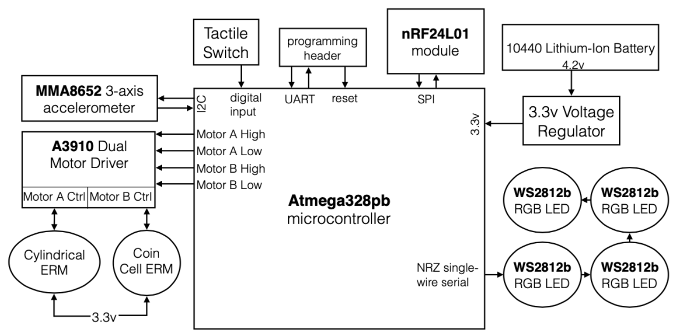


Figure 2: A system overview showing the hardware configuration of a single Vibropixel.

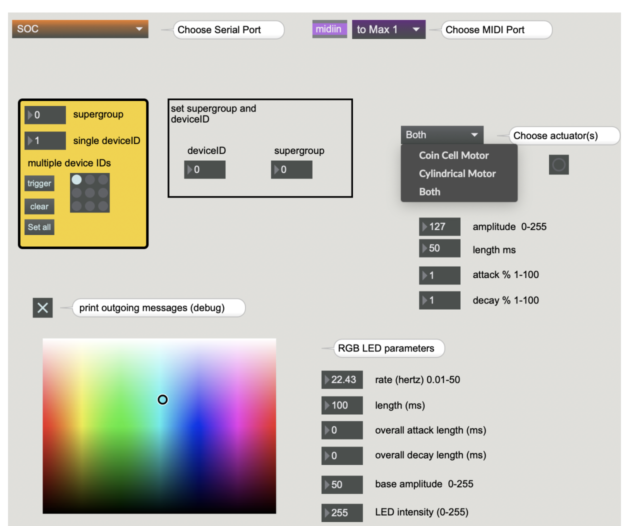


Figure 3: MaxPatch used in the Haptic Tutor.

[1] www.soundbrenner.com

Features of the haptic system

Figure 3 is the presented GUI to set up the Haptic Tutor. The architecture of the system is as follows. The drum teacher feeds in musical notation or MIDI notes into a DAW. On the MaxPatch, we choose the corresponding MIDI bus set in the DAW. Once the DAW playback is on, the MIDI information (MIDI note ON/OFF, note numbers and velocity) is transmitted in real-time to the MaxPatch which generates the vibrotactile signal for the individual haptic actuators. Each MIDI note is mapped to the individual haptic bracelets on the limbs. The technology is very flexible in that, it is easy to reconfigure the network topology on software, instead of having to replace the haptic bracelets between limbs.

In the context of this paper, the students are expected to follow a pre-recorded drum lesson. The haptics is driven by the MIDI information of the drum lesson. A delay correction algorithm is implemented based on tracking intended timestamp of the vibration-triggers and the actual production of the vibration measured by the accelerometers on the Vibropixels.

Ramped-up pre-vibration

To characterize the ramped-up pre-vibrations, we recorded several measurements of drum strokes by a drummer, using an Inertial Motion Unit (IMU) attached to the drum stick. The build-up acceleration towards the end of the stroke when the stick hits the drum has an exponential characteristic. We use this information to characterize the ramping up of the vibration before the occurrence of the peak of the vibration pulse. Though we tried other types of ramp-up pulses like triangular, sinusoidal and parabolic, exponential ramp-ups gave the best sensation of a relatively strong peak at the intended time instant of the drum stroke, from informal tests. The former ramp-ups blurred the peak onset. The peak amplitude was held on for about 30ms for a confident pulse that could be felt. The decay curve of the pulse did not seem to have an effect since the haptic sensation on the limbs caused by the striking of the stick onto the drums masked the effect of the haptic actuations from the Vibropixels. The attack time of the final pre-vibration pulse implemented lasts about 150ms. The pre-vibration also compensates for the fact that we have a certain response time for stimulus-response tasks [20], thus helping us better anticipate drum strokes, in this context.

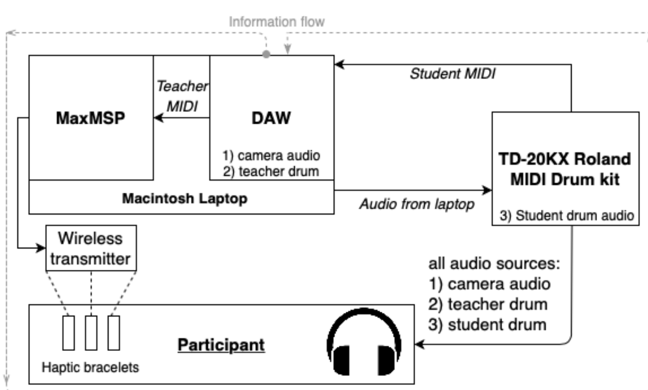


Figure 4: Block diagram of the Haptic Tutor experiment setup.

Technical setup

The teacher performed on a Roland TD-20KX electronic drum kit which included kick, snare and hi-hat.

The setup for the experiment consisted of the following (Figure 4) : a Digital Audio Workstation (DAW) (Apple's Logic Pro X) included the pre-recorded drum lesson and the metronome clicks corresponding to the ideal MIDI ticks (score) as well as the teacher's MIDI data. Once the playback on the DAW starts, it sends the teacher's MIDI data in real-time to the Max patch which parses the MIDI information to drive the Vibropixels (via the wireless transmitter) on the respective haptic bracelets. The ideal MIDI ticks are used to calculate deviation from perfect performance. The bracelets were secured to the student's wrists and right ankle with the use of double-sided velcro straps as seen in Figure 5. The straps were adjusted so the vibrotactile could rest directly on the skin of the participant. We decided to place the vibropixel in between the radius and the ulna, at the base of the wrist. For the ankle, we secured the vibrotactile at the base of the tibia.

The participants follow the drum lesson cues to produce the drum strokes on the MIDI drum kit, cf. Figure 6b. The MIDI information is recorded on the DAW for further data analysis. Each participant has a combination of three audio sources mapped to their headphones: 1) the camera audio (teacher speaking) from the pre-recorded drum lesson 2) the teacher's drum sounds, 3) the student's drum sounds on the TD-20KX module. The student drum tone is chosen different from that of the teacher's drum kit tone so that the student can differentiate their drum strokes from that of the teacher. The audio signals were routed from the laptop via Logic Pro X to the Roland TD-20KX module to the student's headphones. The audio levels where set in order of importance: the student's sound, the teacher's sound, and the camera audio. For control reasons, the student was able to decide on the volume of the lesson.

Figure 5: Haptic bracelets secured to the student's wrists and right ankle.

(a) Screenshot of teacher's video. *(b) Picture of a participant.*

Figure 6: Left: Pre-recorded video lesson. Right: Participant using the Haptic Tutor during the drum lesson experiment.

Pre-recorded drum lesson

To avoid bias in teaching, the students were expected to follow a pre-recorded drum lesson to play the musical material (cf. Appendix). The drum lesson was pre-recorded from a side view to provide a clear view of the teacher's foot and forearm movements, cf. Figure 6a. During the recording of the drum lesson, the MIDI information of the teacher's drum strokes was captured and synchronised to the video timecode.

The lesson included technical advice and various approaches to understand the musical material provided orally by the teacher during the performance. The whole drum lesson was recorded at 80 BPM tempo, as past experiments that compared tactile and auditory conditions used tempos in the range of 60-120 BPM [12]. Audio metronomes usually tick on eighth-note divisions in a given bar. Since the lesson involves only eighth notes, the drum strokes in the lesson aligns with the audio metronome.

Experiment 1

In the first experiment we aim to evaluate the usefulness of providing vibrotactile feedback as part of a very basic drum lesson that only includes the arms, cf. Figures 12 to 14 (**lesson 1** in the Appendix).

Our main hypothesis was that vibrotactile feedback would improve subjects rhythmic accuracy and precision, i.e. their performances will present lower asynchrony and inter-onset interval (IOI) if compared to the non-haptic condition.

A secondary hypothesis was that *the type* of vibrotactile feedback would also have an impact on subjects' asynchrony and IOI measures, i.e. using different vibrotactile stimuli would further impact on their performances. The work of Ignoto et al. [16] proposes that we get a better sense of when the next beat occurs when there is a ramp-up vibration to the maximum peak, in the context of haptic-based music conducting. In this paper we apply this concept of ramped-up pre-vibration to the context of drum learning.

Methodology

A total of 30 participants, all non-drummers, right-handed and aged between 20-28 years took part in the study. None of them have taken drum lessons before, though all participants have played instruments in school programs and private lessons in the past including piano, guitar, violin, voice, among others.

They were asked to play three simple exercises while watching the video of the teacher (cf. Appendix, lesson 1). Figures 12 to 14 present the scores of the drum lesson (the 3 figures correspond to the 3 rudiments respectively, each consisting 100 strokes), which involves a total of 300 strokes.

Participants were split into 3 groups of 10 each, in a randomized manner. Each group underwent one condition: VIDEO (DL), HAPTIC PULSE (P) or HAPTIC RAMP (R), respectively. In the DL condition, the haptics are turned off, and the student follows just the video (and associated audio) of the drum lesson. In the P condition, a momentary burst lasting 30ms is felt when the drum stroke is supposed to be produced [2]. In the R condition, a pre-vibration lasting 50ms is prepended to the pulse for each drum stroke, i.e. there are two haptic stimuli for each stroke. The drum lesson playback video was kept unchanged throughout the experiment for all conditions.

[2]Though a delay correction algorithm has been implemented, we risk the chance of a wireless interference causing a missed vibration. Informal tests have shown that this could happen roughly once in 300-400 strokes, or once in 30 minutes of usage.

Results

The MIDI files were analyzed to extract onset MIDI ticks from the participants' performances. The main measures we looked at are: **miss-ratio**, *accuracy* by measuring **average asynchrony** and *precision* from **IOI deviation** [13, 20, 12].

Miss-ratio

We started by filtering strokes with very poor timing (outliers). In this experiment, given the chosen BPM of 80, the Inter-Onset Interval (IOI) is 750ms. We remove strokes with deviations greater than half an IOI, or 325ms, as well as missed strokes. Such mistakes are classified as *miss-hits*. We then measure **miss-ratio** across conditions [20]. Table 1 shows the percentage of miss-hits to the total number of strokes.

Condition	**DL**	**P**	**R**
Miss ratio %	35.71	15.39	17.75

Table 1: Miss ratio across conditions.

Both haptic conditions (P and R) showed fewer miss-hits than the DL condition, with the number of miss-hits being around half of the DL value. The evolution of miss-hits over the duration of the experiment for the three conditions is shown in Figure 7.

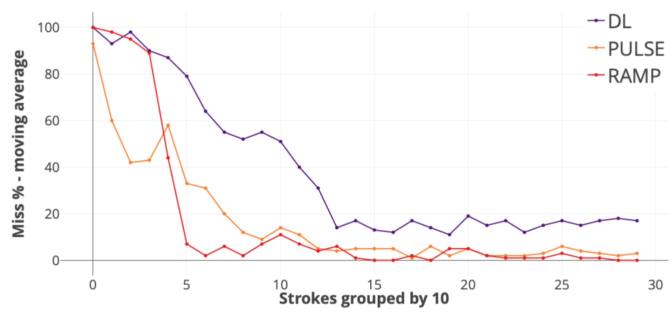


Figure 7: Moving average of miss % for every 10 strokes.

Asynchrony & Inter-Onset Interval deviation

For the calculation of Asynchrony and IOI deviation we removed the outliers as explained before. An asynchrony vector representing participants' lag or delay with respect to ideal MIDI ticks was computed for all the participants by subtracting drum-stroke (MIDI Note ON message) time vectors to ideal MIDI tick time vectors.

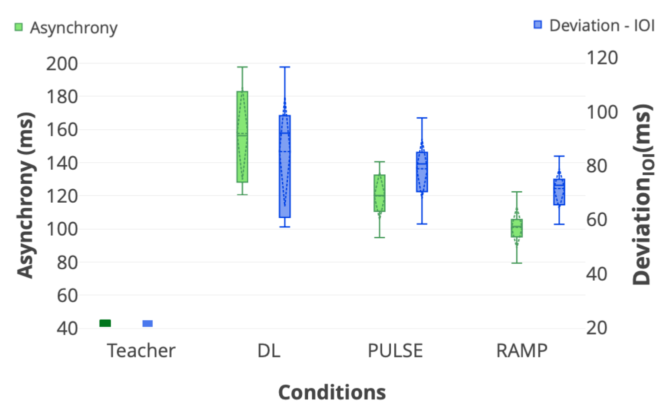


*Figure 8: **Experiment 1**. Box plot illustrating asynchrony mean and IOI deviation in the 3 conditions. Thick lines from top to bottom of each box: max value, third quartile, median, 1st quartile, mix value; dotted lines show mean and SD.*

Inter-Onset Interval (IOI) was determined by calculating the time interval between one MIDI onset (drum stroke) and the following one, averaged over all the MIDI onset intervals.

Table 2 shows the mean and standard deviation (SD) of asynchrony as well as deviation from the target tempo expressed as an IOI across conditions, with box plots shown in Figure 8.

Condition	DL	P	R
Asyn Mean [ms]	157.56	119.88	100.91
Asyn SD [ms]	29.23	15	13.1
IOI Mean [ms]	85.17	78.81	71.47
IOI SD [ms]	21.32	11.60	7.79

*Table 2: **Experiment 1.** Mean and SD of asynchrony and deviation from target tempo expressed as IOI (in ms) across conditions (**DL, P** and **R**).*

When comparing performances of all players, including the teacher for reference, we find that the teacher's performance is the most accurate, with an asynchrony of 43 ms and an IOI deviation of 21 ms. In the P condition, we observe that mean and SD of asynchrony as well as deviation from target IOI were reduced as compared to DL condition. The R condition performed even better than P (smaller mean and SD).

For the analysis of these results, we chose to use 95% confidence intervals (CI) and effect sizes instead of the more common null hypothesis significance testing (NHST)[3], following a trend in several research communities[4]. A detailed discussion of this approach is available at [9].

Table 3 presents the 95% CI for the three conditions, while table 4 shows *Cohen's* $d_{unbiased}$ (d_u) and its 95% CI for comparisons between conditions, i.e. P & DL, R & DL and R & P [9].

Condition	DL	P	R
CI Asyn [ms]	136.65 - 178.47	109.15 - 130.61	91.56 - 110.26
CI IOI [ms]	69.92 - 100.42	70.51 - 87.10	65.89 - 77.04

*Table 3: **Experiment 1.** 95% CI for conditions **DL**, **P** and **R**.*

	P vs DL	R vs DL	R vs P
d_u **- Asyn**	1.6	2.4	1.3
CI - Asyn	0.58 - 2.63	1.29 - 3.68	0.35 - 2.31
d_u **- IOI**	0.4	0.8	0.7
CI - IOI	-0.52 - 1.25	-0.08 - 1.76	-0.18 - 1.64

*Table 4: **Experiment 1.** d_u and 95% CI for pair comparisons **P vs DL**, **R vs DL** and **R vs P**, calculated using ESCI [10].*

Experiment 2

A second experiment was devised to evaluate the effect of vibrotactile feedback with the increase in the complexity of drumming exercises. Naturally the second lesson is harder as it involves the right foot and not just hands like in rudiments. Though we might see that participants find it difficult to cope up with this second lesson, we wish to see if the haptic group coped up better than non-haptic group.

Our hypothesis, similarly to the previous experiment, is that haptics will help beginners to improve their performance if compared to the use of a video example alone. As Experiment 1 showed that the R condition had a lower asynchrony value, as well as slightly better value for IOI deviation than the P condition, we decided to only keep the R condition and compare it to the DL condition.

[3]NHST analysis of Experiment 1 data is available at: https://github.com/IDMIL/HapticTutor/

[4]https://aviz.fr/badstats

Methodology

Sixteen subjects, all non-drummers, right-handed, aged between 20-28 years and who did not take part in Experiment 1 were randomly assigned to 2 groups of 8 subjects each, one playing in the DL condition and the other in the R condition. As in Experiment 1, they were asked to play the five exercises while watching the pre-recorded video of the teacher. Conditions DL and R are the same as in Experiment 1.

Each group was asked to perform the first 3 exercises (**Lesson 1**), and then to perform 2 extra exercises where the right foot is involved (**Lesson 2**, cf. Figures 15 and 16). All exercises are played at 80 BPM.

Results

As in experiment 1, MIDI onset ticks of participant performances were analysed in terms of miss-ratio, asynchrony and IOI deviation.

Miss-ratio

Table 5 shows similar results as in table 1, with a reduction of the number of miss-hits between 10% and 15% for the R condition compared to the DL condition.

Experiment 2, #1	**DL**	**R**
Miss ratio %	28.76	19.23
Experiment 2, #2	**DL**	**R**
Miss ratio %	36.79	23.47

*Table 5: **Experiment 2.** Miss ratio across conditions in the two lessons.*

Asynchrony & Inter-Onset Interval deviation

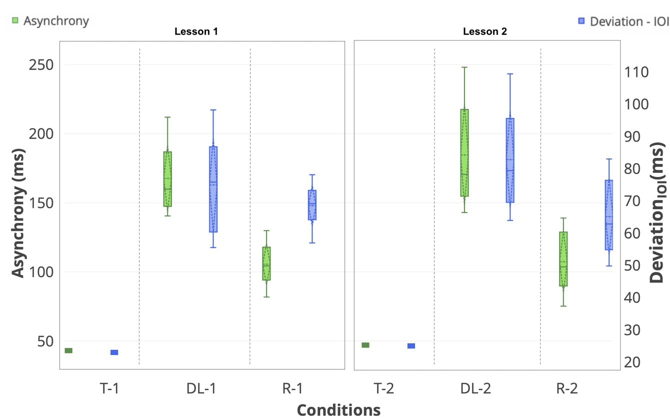


*Figure 9: **Experiment 2**. Box plot illustrating asynchrony mean and IOI deviation in conditions **DL** and **R** for lessons 1 and 2.*

Lesson #, Condition	#1, DL	#1, R	#2, DL	#2, R
Asyn Mean [ms]	167.6	105.56	184.59	107.35
Asyn SD [ms]	25.64	15.9	38.99	23.55
IOI Mean [ms]	74.95	69.5	82.79	65.11
IOI SD [ms]	15.49	6.69	16.16	12.55

*Table 6: **Experiment 2.** Mean and SD of asynchrony and IOI deviation across conditions (**DL** and **R**) for lessons 1 and 2.*

Lesson #, Condition	#1, DL	#1, R
CI Asyn [ms]	146.16 - 189.4	92.27 - 118.87
CI IOI [ms]	61.99 - 87.91	62.91 - 74.1
Lesson #, Condition	**#2, DL**	**#2, R**
CI Asyn [ms]	151.99 - 217.19	87.66 - 127.04
CI IOI [ms]	69.28 - 96.3	54.52 - 75.6

*Table 7: **Experiment 2.** 95% Confidence Intervals for conditions **DL** and **R** for lessons 1 and 2.*

	Lesson #1, R vs DL	Lesson #2, R vs DL
d_u **- Asyn**	2.7	2.3
CI - Asyn	1.46 - 4.33	1.06 - 3.69
	Lesson #1, R vs DL	**Lesson #2, R vs DL**
d_u **- IOI**	0.5	1.2
CI - IOI	-0.47 - 1.53	0.13 - 2.28

*Table 8: **Experiment 2.** d_u and 95% CI for pair comparison **R vs DL**, calculated using the software ESCI from [10].*

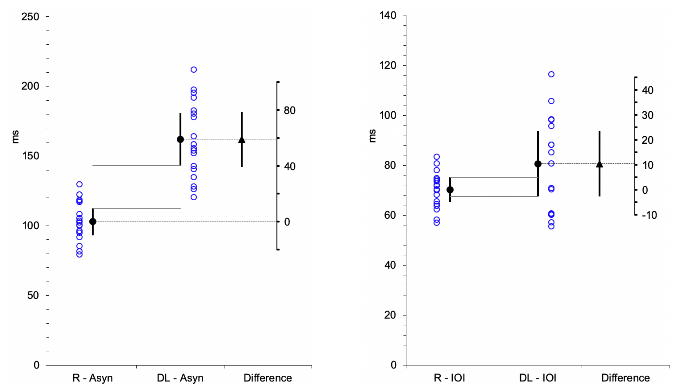
Discussion

Considering Experiment 1, the **miss-ratio results** presented in table 1 show that in the R condition there were several early hits when the participants started using the system, what accounts for the slightly larger percentage of miss-hits in R if compared to P. This seems to indicate that they got confused with the ramp-up trend in the beginning of the experiment. Figure 7 shows that participants improved their performance during the lesson for all conditions, with the highest improvement for the two haptic conditions. In the R condition, participants made drastically fewer mistakes after the first 50 strokes. As the lesson progresses, the R condition turns out to have the fastest rate of improvement and after 100 strokes it is comparable to P. Miss-ratio results in Experiment 2 shown in table 5 display similar characteristics, with much lower values for the R condition in comparison to DL, ranging between a reduction of a third to half of the errors.

Considering **asynchrony**, Experiment 1 results (cf. table 3) support our hypothesis that the use of haptics does impact drum stroke accuracy, the 95% Confidence Intervals showing no overlap across conditions. Asynchrony values for d_u between conditions P & DL and R & DL indicate that there would be respectively 95% and close to 99% chance that a given DL asynchrony performance would rank below the average performance in each of the haptic groups. Effect size for the comparison between conditions R & P indicate a smaller, though still noticeable difference, with around 90% chance that the asynchrony of a given P performance would be lower than the average asynchrony of R performances (cf. Table 1 of [8]). Results for lesson 1 in Experiment 2 (cf. table 7) are very similar, again confirming that the use of haptic feedback (R condition in this case) helped reduce the asynchrony measurement. Asynchrony d_u was similar, though a bit higher than for Experiment 1, and with a positive CI. When considering the more difficult lesson 2 (with the addition of the right foot), again condition R presents much lower asynchrony values if compared to condition DL, with no overlap in the respective 95% CIs. Its d_u value of 2.3 and its positive CI are again comparable to previous asynchrony differences.

Results are not as clear cut for **IOI deviation** in the two experiments. Though there is a pattern of improvement when using the haptic conditions, mostly the R condition, there seems to be no strong difference across conditions. In Experiment 1 (cf. table 3), the 95% confidence intervals for the three conditions overlap, what leads to much weaker d_u values for the comparisons between conditions, all of them below 0.9. Similarly results were obtained for lesson 1 in Experiment 2 (cf. table 7), with low d_u values and CIs including negative values. This can also be seen in Figure 10, which shows the comparison of asynchronies (left) and IOI deviation (right) for R and DL conditions for all subjects in both experiments (36 participants). Finally, two points can be made about IOI deviation results:

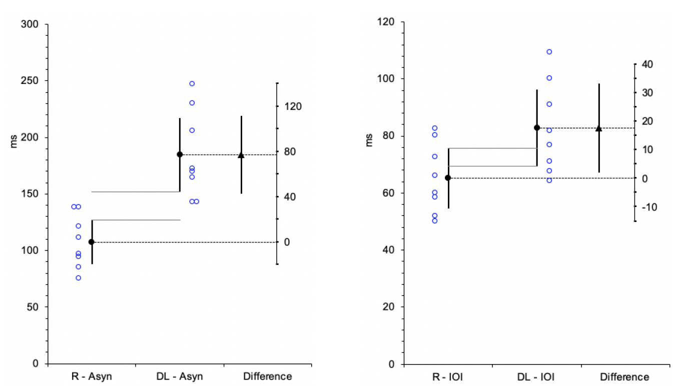
- In lesson 1, although 95% CIs for the three conditions overlap, they do mostly so in lower values of the interval. Upper values are rather different between conditions (i.e. reduced intervals for P and R).
- Contrary to lesson 1, the lower right cell of table 8 shows a d_u value higher than 1 with a **positive** CI, meaning a stronger effect of condition choice on IOI for lesson 2.



(a) Asycnhrony. *(b) IOI Deviation.*

*Figure 10: **Results including all participants playing Lesson 1 (Experiment 1 & Experiment 2)**, 36 subjects total. Comparison of conditions **R** and **DL**. Performance data (blue empty circles), Mean and 95% Confidence Intervals for conditions **R** and **DL** (dark full circles) and the difference between them (dark full triangle) with CI. Note the very clear improvement for the asynchrony in R, but less so for IOI deviation.*

The first point suggests that the haptic conditions, and specially the R condition, help performers keep strike precision within a relatively smaller range than in the DL condition. The second point tends to show that adding haptics help subjects improve IOI precision in more complex lessons (cf. right side of Figure 11), though less so for simpler ones.



(a) Experiment 2, #2, Asynchrony. *(b) Experiment 2, #2, IOI.*

*Figure 11: **Experiment 2, lesson 2.** Comparison of conditions **R** and **DL**. Performance data (blue empty circles), Mean and 95% Confidence Intervals for conditions **R** and **DL** (dark full circles) and the difference between them (dark full triangle) with CI. Note the clear improvement for asynchrony, but also an improvement for IOI deviation.*

The R group coped up better with the increase in difficulty from lesson 1 to lesson 2 (addition of foot) than DL group. There was not much difference in the results between the first (one foot, one hand) and second (one foot, two hands) exercise of lesson 2 . The addition of the foot strokes was the new/confusing part for the participants.

Subjective evaluation

In this section we summarize the responses of the post-experiment survey taken by the participants.

The participants in the DL group generally mentioned that it took a large amount of time to cope up with the lesson, especially lesson 2 for which they found it really hard to perform the foot strokes. They particularly found it hard to focus on the limb to be used for the strokes in lesson 1 as this lesson involves very specific orders in which the left and right hands have to perform each drum stroke. DL participants ended up trying to make *some* stroke whenever they heard a drum stroke without caring about the limb to be used.

In general, all participants of the haptics groups expressed their interest in using the haptic system; they were excited to try something "new" which they would not find otherwise in a traditional music lesson. All but two participants (26) who tried one of the haptic conditions responded that haptics-aided music lessons are certainly useful, especially in the context of developing "rhythm sense". All but 2 participants from experiment 2 haptics group (6) commented that they felt they got better over time, though they lacked confidence in their foot strokes in lesson 2.

All the participants found the VibroPixels comfortable to wear on the limbs, with the remark that, if they played too hard, the bracelet could slip off making them extra-cautious during a performance. 5 students would prefer a more comfortable material than the double sided velcro straps used to secure the vibrotactiles. 9 participants pointed out that they could not feel the vibrations in their legs as strongly as they could feel them on the arms, a similar result to [15].

Several users in the P condition complained that feeling the haptic stimuli and the haptic feedback of striking the drum at the same time was odd. Some wished that the hit would precede the drum stroke so they would already know which limb to move before the hit. The participants of the R condition did not face this issue as they had a pre-vibration. However, some of them did complain that they ended up preparing and finishing the stroke earlier than required. Also, in the R condition, all the subjects reported they took a while to get used to the exact onset of onset peak of the vibration that corresponds to the stroke onset, what can be seen in Figure 7. But once they figured out the trend of the ramp-up, they developed a better sense as to when to start producing the preparatory actions for the strokes.

What participants liked most about the haptics system was that they would know right away when they made a mistake or when they missed a beat. Moreover, some of them would stop playing and feel the haptics on each limb to understand the coordination of the musical task. 24 participants would like the Haptic Tutor as a "virtual teacher" for when they would practice at home. 3 said that they would want to program an entire song on MIDI and to include it in a game setting much like the game 'Rockband'. 9 participants suggested that they would like to control the characteristics of the vibrations; several pointed out possible improvements in "sharpness" and "strength". Finally, 7 participants proposed a limb-specific normalization of strengths.

Conclusion and Future Work

This paper introduced Haptic Tutor, a wearable system for delivering haptic feedback during drum lessons. Two experiments validate the hypothesis that haptic stimuli improve temporal characteristics of drum lesson performances, with a clear improvement for accuracy (lower asynchrony means) and a modest improvement for precision (IOI deviation mean), though with both measures presenting marked reduced variability in the haptic conditions compared to the baseline condition (DL). The experiments also validate our secondary hypothesis that the type of haptic stimulus has an influence on performance with a clear reduction of asynchrony means and lower variability of IOI deviation in conditions P and R. Furthermore, results from lesson 2 clear also showed an improvement in IOI deviation mean for the R condition, what suggests the usefulness of the system in more complex exercises (i.e. involving a third limb). Subjective evaluations were generally positive, with very few limitations pointed out.

As a future work, we would like to further investigate, fine-tune and present the characteristics of our ramped-up haptics. We wish to conduct a follow-up study in which we continue the drum lessons with the same participants and observe retention of their rhythm production across conditions. We also aim to build experiments around the feature of our haptics system being able to work in a live-teaching mode: teachers wear the VibroPixels too and their motions are translated to vibrations on the student's VibroPixels in real-time. We would also be interested to test our system on the students with learning/visual/hearing disabilities.

Links to extended results and videos :
https://github.com/IDMIL/HapticTutor

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APPENDIX

THE DRUM LESSON

The teaching material includes 2 lessons:

Lesson 1 : Rudiments

The first lesson is a simple two limb coordination lesson to help the student develop independence. In this lesson the student will play the three most basic rudiments: Single stroke roll, Double stroke roll, and Paradiddle.

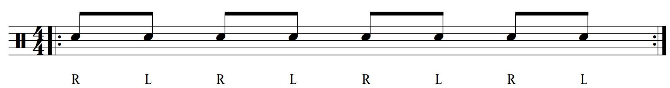

Figure 12: Single stroke roll (RLRL...)

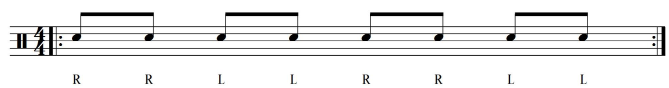

Figure 13: Double stroke roll (RRLL...)

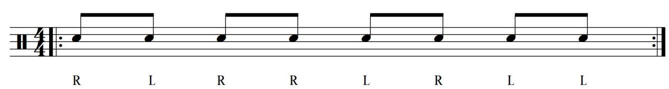

Figure 14: paradiddle (RLRRLRLL...)

Lesson 2 : Linear beat

The second lesson is the introduction to a linear beat, commonly heard in disco music. In drumming, linear represents a single line sequence or a horizontal way of playing where no two hits occur at the same time. The first layer is the fundamental kick to snare relation: Kick is on beats 1 and 3; snare is on beats 2 and 4, cf. Figure 15. The second lesson adds the eight note hi-hat beats between snare and kick drum hits, cf. Figure 16.

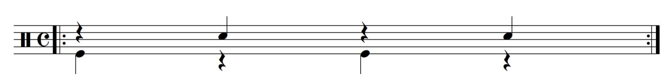

Figure 15: The fundamental kick to snare relation

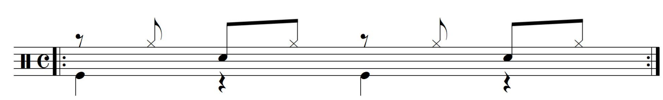

Figure 16: Linear beat: the fundamental kick to snare relation and the hi hat on all up beat eight notes