Karlsruher Institut für Technologie

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Teaching Rhythm via Passive Haptic Learning

Bachelor's Thesis

by

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Karlsruher Institut für Technologie

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Bachelorarbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel und Quellen benutzt habe, die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und weiterhin die Richtlinien des KIT zur Sicherung guter wissenschaftlicher Praxis beachtet habe.

Karlsruhe, den 28.04.2022

Abstract

This thesis is concerned with teaching participants of a research study a simple rhythm through the use of haptic and/or auditory signals and having them replay it from memory. The learning of the rhythm will happen passively, meaning the participant of the study will be distracted by an independent and unrelated task while learning.

Another aspect considered, is the tool used by the participant to play the rhythm. For this matter, all test subjects will have to use both a keyboard as well as a ukulele to play the rhythm. We compare how the different types of signals received during the learning phase affect the timing and duration of notes when the rhythm is played. These signals will be either haptic, auditory, or a combination of both. We will also calculate how consistently the participant can recall the rhythm. This study will only evaluate the temporal aspects of rhythm, meaning it will not matter what types of notes (e.g. A, F#, g) are played.

We will find that the difference in instruments and learning groups will be of significance when looking at the duration of notes and pauses, however, only the difference in instruments will be significant for the aspect of timing. We will further find that within the groups, the difference in instruments will usually also be of statistical significance.

Deutsche Kurzfassung

Diese Arbeit befasst sich damit, Teilnehmern einer Forschungsstudie einen einfachen Rhythmus durch Benutzung haptischer und/oder auditiver Signale beizubringen und die Teilnehmer diesen aus Ihrer Erinnerung spielen zu lassen. Das Lernen des Rhythmus wird passiv stattfinden, was bedeutet, dass die Teilnehmer der Studie durch eine unabhängige und unzusammenhängende Aufgabe abgelenkt werden, während sie lernen.

Ein weiterer Aspekt welcher betrachtet wird, ist welches Instrument der Teilnehmer benutzt um den Rhythmus wiederzugeben. Hierbei werden alle Probanden eine Tastatur sowie eine Ukulele verwenden, um den Rhythmus zu spielen. Wir vergleichen wie die verschiedenen Signale, welche die Versuchsperson während der Lernphase erhielt, das Timing sowie die Länge der Töne welche von der Person gespielt werden, beeinflusst. Diese Signale sind entweder haptisch, auditiv oder eine Kombination aus beidem. Ebenfalls wird betrachtet wie gleichmäßig die Rhythmen vom Probanden gespielt wurden. Diese Studie wird sich nur mit den zeitlichen Aspekten von Rhythmen auseinandersetzen, es wird sich also nicht betrachtet welche Art von Note (z.B. A, F#, g) gespielt wird.

Betrachte man die Länge der Noten und Pausen, wird eine statistische Signifikanz zwischen den unterschiedlichen Instrumenten, sowie zwischen den unterschiedlichen Lerngruppen gefunden. Bei dem Timing der Noten ist nur eine Signifikanz zwischen unterschiedlichen Instrumenten auffindbar. Zusätzlich werden wir herausfinden, dass innerhalb der Gruppen ebenfalls signifikante Unterschiede zwischen den Instrumenten gefunden werden, egal ob Länge oder Timing der Noten betrachtet wird.

Contents

1. Introduction

Passive Haptic Learning (PHL) is the process of training to perform a certain task without paying attention to it. [LuVS18] There have been many studies concerned with applying PHL to a variety of actions, for example learning Morse code [SRHSS16] or playing the piano [SeES15]. These studies showed great results in teaching the user, without him having to focus on the learning process.

Many PHL studies have concerned themselves with confirming whether the learned movement itself is correct, such as moving the right finger when recalling a piano song [DoPB21] or correctly associating patterns with the haptic feedback, for example, Braille [SCDD+14] or Morse code [PPSB19]. This study will be focusing on the temporal aspect of the learned task, as well as the transfer onto a new context. This will be realized by teaching the user a rhythm, letting them reproduce it on a keyboard, and afterward on a ukulele.

When starting out with learning music, a key component is the understanding of rhythm. It is important to note the difference between what is considered a pulse and what is a rhythm. The pulse is a steady beat that can be measured in time by counting the number of beats per minute (BPM). Usually, the pulse of a song does not change and can thus be considered constant. A rhythm is a pattern of sounds, with varying length, intensity, and pauses in between. The length of said sounds is dependent on the pulse, as the BPM dictates how long a note is played.
This study will follow the norms of music and teach the participants a rhythm that could be part of a generic song, rather than having notes and pauses without any coherence.

2. Background & Related Work

2.1 Related work regarding the learning and teaching of rhythms

Teaching rhythm via haptic signals has been tried before, usually resulting in very good outcomes when it comes to showcasing the effect that the haptic signals had on learning. Some studies [EHSI$^+$17][EbHO18][KaTT15] tried teaching rhythms using electrical muscle stimulation and were successful in doing so. "Stimulated Percussions: Method to Control Human for Learning Music by using Electrical Muscle Stimulation" [EHSI$^+$17] explains the action of a person producing a rhythm through the following process flow:

1. The person looks at the notes and/or listens to the sounds.
2. He or she understands the rhythm in his or her brain.
3. His or her muscles move.
4. Sounds are produced by the musical instrument.

Ebisu et al. argue that people who are not trained in music usually struggle with understanding the correct rhythm when only relying on visual or auditory information. For beginners to understand the rhythm, an experienced teacher or additional training tools are necessary. The authors suggest that using electrical muscle stimulation (EMS) might help people to subconsciously understand the rhythm and be able to properly reproduce it. The process flow used for the conducted study looks as follows:

1. Computer provides rhythm information as muscle electrical stimulation.
2. Muscles move (subconsciously).
3. Sounds are produced by the musical instrument.

4. The brain understands the rhythm.

5. Muscles move

6. Sounds are produced by the musical instrument.

In their user study, EMS pads were attached to the participant's arms and legs, and electrical stimuli were sent to the participant's muscles to get them to move. Afterward, the test subjects were asked to play the rhythm without having any signals. Six out of the twelve participants were able to correctly reproduce the original rhythm. Each participant also learned a different rhythm without EMS and produced significantly worse results. Ebisu et al. concluded that the subconscious learning of rhythms is very effective, especially if the user is a beginner in music.

In "T-RHYTHM: A System for Supporting Rhythm Learning by Using Tactile Devices" [MiSu05], Miura and Sugimoto designed an armband that receives signals from an external transmitter and vibrates for the specified time and strength. Their study consisted of having their test subjects play rhythms on a synthesizer under three different conditions.

The first was playing the melody while listening to it through speakers. The second was playing while a metronome gave off a constant pulse, the third one playing the rhythm while the previously mentioned armband was giving haptic signals. Their finding was that the timing of the played rhythm was matching the actual melody best when the participant relied on the haptic signals of the armband. When the armband was later tested again in an elementary school [MiSu06], the results were once again confirmed, and the responses of the students and teachers were overall positive.

This study will take a similar approach in distinguishing the results of replaying a rhythm, depending on whether auditory or haptic signals were used to learn. The two main differences will be that in this study, the rhythm will not be played by the test subject while he is getting sent auditory/tactile signals, but instead afterward. The second distinction is that instead of differentiating whether a rhythm or pulse is given as auditory feedback, I will also be looking at the learning effect of combining both auditory and haptic signals.

Miura and Sugimoto conducted a second experiment in their study, this time having the participants perform in an ensemble, instead of on their own. The experiment was once again within-subject, this time not using three different learning conditions but four.
As in the previous experiment, the first condition was hearing the melody of the song through speakers and the second one was having a physical metronome give the pulse of the song. The third condition was using a virtual metronome, which did not emit sounds in a constant pulse like the physical one, but instead made a sound every time a new note was played in the original song. The last condition was receiving only haptic signals.

When taking a look at the results of this experiment, similar results to the previous one can be found. In both timing and duration of the played notes and pauses, the haptic signals were the condition that produced the best results.

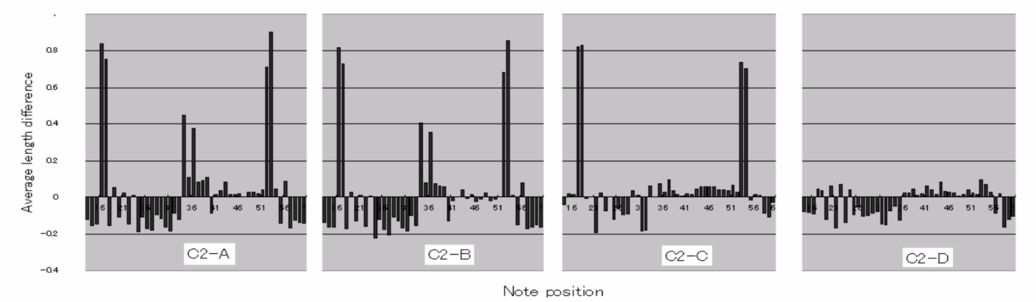

Figure 2.1: Average length differences of each note. C2-A refers to the learning condition of hearing the melody, C2-B to the physical metronome, C2-C to the virtual one and C2-D to the haptic signals.

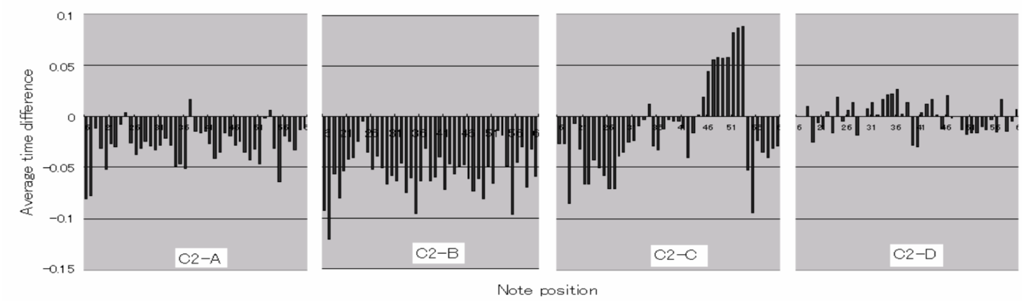

Figure 2.2: Average timing differences of each note. Graph labels are the same as in Figure 2.1.

"An Interactive Music Learning System in Ensemble Performance Class" [TaSa11] by Takano and Sasaki is a study taking an entirely different approach to the previously mentioned studies when it comes to teaching rhythms to participants. They tried combining auditory and visual cues to help the test subject learn the given note sequence, by first having the participant listen to the rhythm and then having him replay it by swinging acceleration sensors. These sensors were connected to a computer that was recording each movement and showing the participant a virtual CG instrument that gave visual feedback on how the movement of the sensors was affecting the timing of a created sound. In this case, the virtual instrument was realized by a ball bouncing in between several blocks, making a sound each time the ball touched a block.

Since the instrument was of a virtual sort, different sorts of sounds could be produced, while the actual motion performed by the test subject stayed the same. These different contexts were then found to have an impact on the performance of the participants. In this study, the performed "context-switch" will be of different nature, simply changing the instrument the rhythm is played on, and later comparing the results.

In "Rhythm Learning with Electronic Simulation" by Stanley and Calvo [StCa09], the authors taught their participants to play the drums, using a simulated drum kit and the video game "Rock band" to provide visual and auditory signals. In their study, the subjects were asked to play the game, which meant playing the simulated drum kit until they reached a score of at least 90%. They also tracked the participant's results, when using only visual or audio signals. They found that the visual feedback was only useful for having the subject play the correct part of the drum, and only slightly affected the rhythm played.
Afterward, they had their participants, who never played the drum kit before, play the game on a real drum set, while using an audio recording of the performance for evaluation. They found that "while the performances were not perfect, they were very good", concluding that performing a switch of the tools used to learn a rhythm and replaying it, produces satisfying results.

2.2 Related work regarding Passive Haptic Learning

When looking at the background of Passive Haptic Learning, it becomes clear that the fields to which PHL can be applied are very broad. The used hardware and desired results of the studies differ greatly and can reach from Google Glasses that teach you Morse code [SRHSS16] to gloves that help you to perfect your typing skills [SeQS14]. There are four studies in particular that conducted experiments that are closely related to this study's procedure.

The first is "Investigating Retention in Passive Haptic Learning of Piano Songs" by Donchev, Pescara and Beigl [DoPB21]. They used a glove, which had a vibration motor mounted onto each finger, to teach their participants how to play the piano. In their study, the subject had to wear the glove while playing a video game. The glove continually vibrated, each vibration resembling a note and each finger representing a different key on the keyboard that needed to be pressed later.

An important aspect of the study was the avoidance of overlearning. Overlearning means that a participant keeps learning after already having achieved a 100% recall in the same learning session. By stopping the learning process after a participant reached 90% accuracy on the recall, overlearning was avoided.

The user study was divided into several phases. First, the participants were able to familiarize themselves with the MIDI-Keyboard, afterwards, a pretest was performed to determine their unfamiliarity with the note sequences.
During the first session, the participants learned a note sequence actively by watching the keyboard play it, while a LED strip showed which keys had to be pressed in order to replicate the note sequence. Afterward, the subject got three attempts to correctly play the sequence. If two of the three attempts achieved an accuracy of over 90% the participants moved on to the next phase, otherwise the process was repeated.
In the next learning phase, instead of actively trying to learn the note sequence, it was instead done passively. This means that the subject wore the glove and played a video game while haptic signals were sent by the glove via vibration, as well as

listening to the sequence. After 20 minutes the participant was asked to replicate the note sequence without receiving any further haptic or auditory signals. As in the previous phase, if the accuracy was below 90% the process was repeated.

Three days later the second session of the study took place. The same participants were asked to play the note sequences previously learned in the first session. This was first done in an unaided test, where the participant had to entirely rely on their memory to replicate the sequence. Afterward, an aided test was done, where the participant was able to see the sequence played on the MIDI keyboard via the LED strip, before having to replicate it again. For each test the subject was given three attempts, the best one being used for evaluation.

When taking a look at the results of the study, we find that the average number of attempts for passive learning is approximately two. This is considerably lower than the number of attempts needed for active learning, which was approximately five. However, it has to be considered that the average learning time of the passive process is longer than the active one, with an average of 42 minutes spent on learning the note sequence compared to 3.8 minutes for the active learning process.
Comparing the number of mistakes made when recalling the original sequence in the second session, shows that when the participants had to recall the sequences in the unaided test, no significant differences could be found between the actively and passively learned melodies. When comparing the results of the aided test, however, it becomes apparent that the passively learned sequence could be replayed by the subject with a significantly higher accuracy rate.

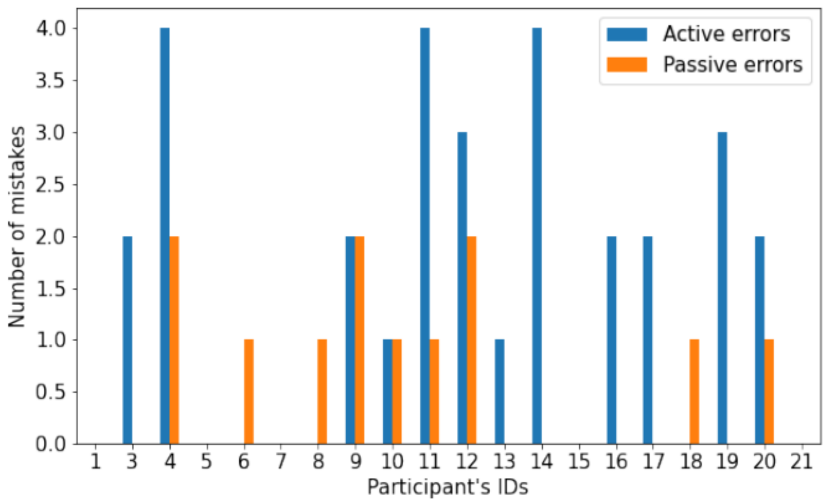

Figure 2.3: Mistakes per subject on the aided recall.

Different from this study, the independent variable in their case was the order of keys pressed on the MIDI keyboard, instead of the timing and length of the sound as here. Another aspect of Donchev et al.'s study was the retention of actively and passively learned note sequences. This will not be considered in this study.

Another important study in the field of Passive Haptic Learning regarding teaching musical skills is ”Mobile Music Touch: Mobile Tactile Stimulation For Passive

Learning" [HSDW+10]. The used hardware was once again a glove using different vibration motors for each finger. Huang et al. compared how well the participants were learning given note sequences actively, compared to passively. In this case, active learning refers to watching LEDs light up on different keys of a MIDI keyboard and hearing the note sequence play. The subjects were asked to then replicate the said sequence. Passive learning refers to learning the piano piece by listening to audio signals and receiving haptic feedback from the glove. Overall, passive learning proved to be more effective in teaching the test subjects the note sequence.

In another experiment by Huang et al., the participants were divided into two groups, one getting auditory and haptic signals while being distracted by a reading comprehension, the other one only having only auditory signals. The tracked independent variables, in this case, were both the order of played notes as well as the rhythm. When looking at the results of tactile vs non-tactile regarding the number of errors in the played note sequence, tactile is the clear winner with 15 out of 16 people performing better with the help of tactile signals. When looking at the rhythm however, the results are not as clear with eight out of 16 people doing better with the help of tactile signals, while the other eight were doing better without any tactile cues. To evaluate the error of the played note sequence, as well as the timing of the rhythm, the Dynamic Time Warp (DTW) algorithm was used.

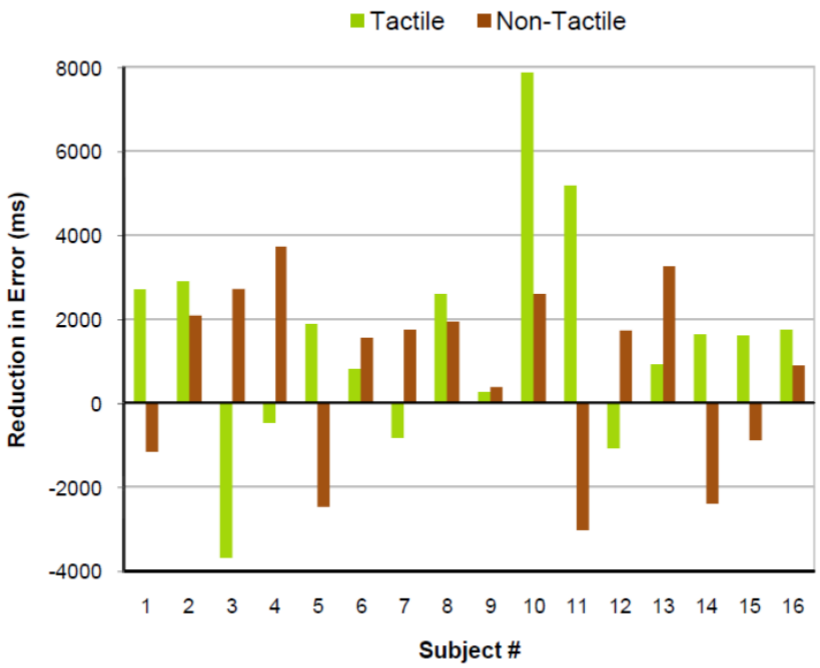

Figure 2.4: Calculated DTW error per subject for both the haptic as well as the auditory note sequences.

Huang et al. used a two-tailed paired t-test to calculate whether or not the findings regarding the rhythm are of statistical significance. A p-value of 0.437 shows that this is not the case. The authors hypothesized, that the errors in rhythm stem from the participant "stalling" for time when trying to remember which note to play next. They named one example where a subject held a half-second note for roughly four seconds while trying to remember the next notes. It was also hypothesized that the results may differ when the participants are asked to make the rhythm a priority and not hesitate at any moment.

In a follow-up study "Mobile Music Touch: The Effect of Primary Tasks on Passively Learning Piano Sequences" [KoSt10], the authors tried finding correlations between the primary task a test subject had to perform while passively learning a note sequence and their accuracy when replicating it.
The three primary tasks used in this study were

1. Watching a movie.

2. Playing a memory game.

3. Walking a path.

Comparing the results of all three tasks did not suggest any statistical significance, and a NASA TLX test showed a similar workload score for every task. A post-hoc analysis suggested that while the average performance does not seem to differ, individual differences between tasks could be found, however a more focused study was needed to confirm these findings. The authors concluded that Passive Haptic Learning is useful for training manual tasks in several everyday situations.

The third study which had a great impact on how this study was designed is "The Haptic Bracelets: Learning Multi-Limb Rhythm Skills from Haptic Stimuli While Reading" by Bouwer et al. [BoHD13]. The hardware here differs from previously mentioned studies. Instead of a glove, multiple vibrating bracelets were worn around each wrist and ankle by the test subjects. The instrument/tool used to track the rhythm was also not a piano or keyboard but a drum set. After the study was conducted, a semi-structured interview was held with each participant of the study. This was done in order to find design flaws in the PHL device, as well as to get user feedback on Passive Haptic Learning in relation to music. The design of this study's interview was heavily influenced by the interview structure of Bouwer et al.

The last relevant study is "Towards Passive Haptic Learning of Piano Songs" by Seim, Estes, and Starner [SeES15]. Here the subjects were divided into three different groups, one getting tactile feedback by a glove, the second one receiving only auditory signals, and the final one having both combined. Each group got 30 minutes to learn a 22-note music sequence, which was an extract from either "Jingle Bells" or "Amazing Grace". The Dynamic Time Warp algorithm was then used to check each group for their mean difference error when recalling the rhythm and playing it on a MIDI piano. The group which only used auditory signals to learn the song performed the worst, the other two groups had the same overall error rate. Since the DTW algorithm was used, there is no exact data on how much the (temporal) rhythm of the different groups differ, since the error rate was mostly dependent on whether or not the correct note was played.

2.3 Differences to previous work

The purpose of this study is to gather data on an aspect that has often been ignored or under-analyzed in previous studies that tried teaching musical skills via Passive Haptic Learning: Rhythm. While it is obviously important to press the correct key on a piano when playing a song, it must also be considered that the timing and length of the played notes must match the tempo and notation of the original song.

The following points are the main differences between this study and the studies mentioned in the previous Background & Related Work section.

1. The studies which divided their subjects into several groups conducted within-subject studies. This study will instead be between-subject, differentiating and comparing the results of the groups, which have no overlapping members. This is done for several reasons, the first one being that if the study would be within-subject, each participant would spend roughly three times as much time on the study as with the between-subject design. The shorter time helps with the test subjects agreeing to participate in the study in the first place, as well as making it less likely that they quit during the conduct.
   The second reason is that a between-subject study design negates any learning processes between switching groups and using the knowledge from the previous task in the next one. On the other hand, if the participant has to learn two different rhythms, it might be possible that he confuses them, causing him to make mistakes in the second rhythm that would not have happened if it had been the first one.

2. Another key difference to the studies using a glove is, that in this study, while a note sequence exists and is taught to the participant, it does not matter which fingers are used when reproducing the rhythm on the keyboard. For example, if on the glove, the first two haptic signals would be the thumb and pointer finger vibrating, the test subject could only use their ring finger to play the sequence on the keyboard without having any influence on the result, as only the timing and length of the key-press count. When playing the rhythm on the ukulele, the participant is also allowed to use any number of strings but is encouraged to only use a single one to avoid making any "clumsy" mistakes.

3. When the participant plays the rhythm on the keyboard, he will be given no audio feedback. This is done in order to see how the user perceives the rhythm when he can't hear it when playing it himself and only gets haptic feedback even while reproducing it. This will be especially interesting when the user also only got haptic signals sent during the learning phase, as he will have no additional information memorized while playing the rhythm on the keyboard.

4. A part of this study is the transfer of the learned rhythm into a new context. This means that the subject will have to play the sequence on a ukulele, using a very different motion from the key-pressing which is done beforehand. When a string on the ukulele is strung, the participant will have to differ between playing the same string again if two notes follow each other directly, or holding the string still if a pause is next. This is done in order to confirm whether the test subject is only recalling memories of the vibration on his fingers and

moving them accordingly, or if the rhythm has been truly "understood" by the participant, which would ideally be the goal when trying to learn music.

2.4 Outline

The remainder of this thesis is organized as follows:

Chapter three will first give an overview of the hardware. Afterward, an explanation will be provided on how the participants are divided into different groups and what each group has to do. The study design will be explained in greater detail, e.g. how / why was the rhythm chosen or how different notes are mapped onto different fingers. The general procedure of the study will also be explained further.

Chapter four will show how the results of the study were recorded, evaluated, and analyzed.

Chapter five will draw a conclusion on the findings of this study and propose suggestions for future works.

The Appendix consists of several tables showing the exact data recorded in the study.

3. Methods

3.1 Hardware

The PHL glove consists of five vibration motors mounted onto a stretching cotton glove, as well as a BLE Nano v2 chip and a battery. Two of the vibration motors are located on TLC boards (TLC59711), which are sewn face-down onto the ring- and pointing finger of the glove. The other three vibration motors are magnetically attached to the glove, as there are small magnets on the three remaining fingers of the glove. The diameter of a vibration motor is 10mm, its height is around 3mm. The vibration frequency is approximately 200Hz.

All of the vibration motors are located on the intermediate phalanges of the fingers, as done in "Mobile Music Touch" [HSDW$^+$10]. Since the thumb does not have an intermediate phalanx, it is instead located on the bottom of the distal phalanx. It was important to ensure that the cables connecting the various vibration motors are not taut, in order to not have any vibrations carry over from one finger to another.

The BLE Nano v2 chip and battery are attached to the back of the glove, to provide easy transportability and free hand-movement without interfering with any of the haptic signals sent by the vibration motors. To attach the battery and chip, velcro stickers were used, so they could easily be removed from the glove to be either replaced in case of the battery or provide easier access to the USB dongle when connecting the glove to a PC to boot up the program used to vibrate the motors for the correct duration and at the right time. With all components attached, the glove weighs a total of 49 grams.

The BLE Nano v2 chip is able to receive commands for the vibrations via BlueTooth, however, this functionality was not used in this study, as the vibrations provided were constant, and no "on the fly" changes had to be made at any point during the study. The risk of the glove not receiving the signals and thus not vibrating/playing the wrong rhythm was completely negated.

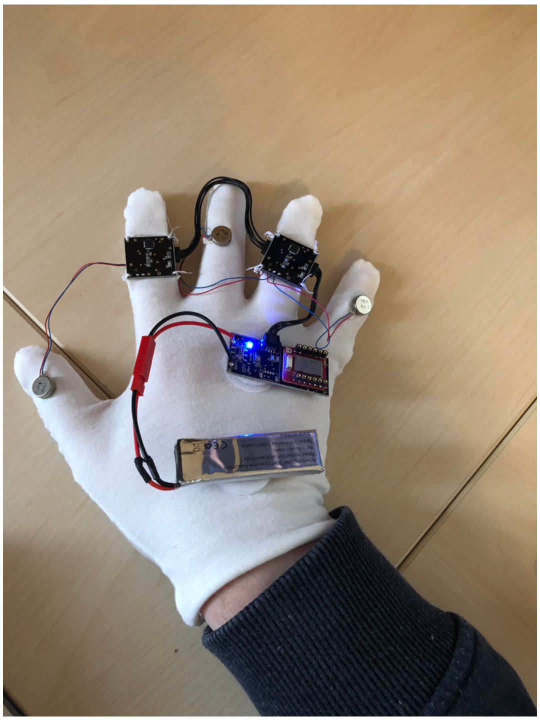

Figure 3.1: A picture of the glove when worn.

The Ukulele used, is of Soprano size meaning a length of 53cm, and is made of wood. It used the standard gCEA ukulele-tuning.

Figure 3.2: The ukulele used in the study.

The keyboard used in the study is mechanical, having Cherry MX Red switches built-in. These switches require very little force to push down, producing no "clicking" sound when pressed, as well as not having a tactile bump when registering the keypress. The travel distance of a key is four millimeters, registering a keypress after two millimeters.

3.2 Participants

To conduct this study, three groups of participants had to be created, to test the rhythm learning process in accordance with the independent variables as well as their combination. The groups are as follows:

Group *Hap*: Learning the rhythm only via Passive Haptic Learning

Group *HapAud*: Learning the rhythm via both Passive Haptic Learning and auditory signals

Group *Aud*: Learning the rhythm only via auditory signals

Each group consists of eight participants, with each group having a roughly equal amount of people who have had experience with music before. This is very important as Yee, Holleran, and Jones found that "in detecting small timing changes in simple acoustic sequences, musical skill aids listeners primarily when meaningful pattern structure can be exploited." [Yee 94]
Since the rhythm learned in this study can be considered a standard pattern in music as seen in Figure 3.3, musicians would likely have an advantage in reproducing said rhythm and the groups need to be balanced. Out of the 24 participants, eight were female and the other 16 were male.
As mentioned in section 2.3, this study is between-subject, comparing the results between the different groups.

ID	**Musical experience**	**Instrument**	**Experience**
A01	yes	Guitar/French Horn	14 Years
A02	no		
A03	yes	Piano	2 Months
A04	yes	Piano	10 Year
A05	yes	Violin	9 Years
A06	no		
A07	yes	Piano	5 Years
A08	yes	Piano	8 Years
B01	yes	Guitar	1 Year
B02	yes	Piano	3 Months
B03	yes	Piano	6 Years
B04	yes	Violin	14 Years
B05	no		
B06	yes	Drums	4 Years
B07	no		
B08	yes	Flute/Piano	5 Years
C01	yes	Piano	5 Years
C02	no		
C03	yes	Piano accordion	5 Years
C04	yes	Guitar/Recorder	8 Years
C05	no		
C06	yes	Piano	3 Years
C07	yes	Piano accordion	3 Years
C08	no		

Table 3.1: Participants identified by their ID and their musical experience. IDs starting with "A" refer to group *Hap*, "B" to *HapAud* and "C" to *Aud*.

3.3 Study Design

The design of this study is heavily based on previous Passive Haptic Learning studies which used a glove to teach subjects how to play an instrument, in this case, "Mobile Music Touch" [HSDW+10] and "Investigating Retention in Passive Haptic Learning of Piano Songs" [DoPB21]. The length of the taught rhythm and the amount of time spent passively learning it are both chosen based on the note sequences used in previously mentioned studies. This is done to prevent the participants from over-learning the rhythm during a single learning session, while still giving them enough time to actually show results when trying to reproduce the learned actions.

When considering which primary task the test subjects should have to perform, I once again went with the "Investigating Retention in Passive Haptic Learning of Piano Songs" choice and only allowed the participants to play a video game, instead of choosing between programming, performing office work or playing a game as in "Mobile Music Touch".

The note sequences used in those studies did not feature a large variety in note lengths as well as no pauses in between different notes and were thus unfit for this study. The rhythm used here was specially designed for this use and has notes and pauses of varying lengths to check if the user can tell the difference between them. It is important that the used note sequence is not a snippet from any commonly known song, as that might incur a bias for some participants who know or even played that musical piece before.

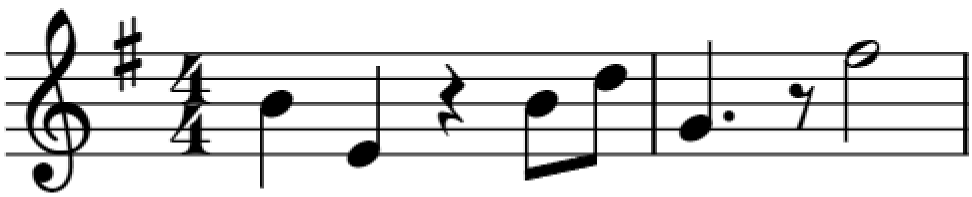

Figure 3.3: Note sequence used in this study, using a total of four different note and pause lengths.

The speed of the rhythm was set at 150 beats per minute which means the following length for each of the notes and pauses:

200ms: ♪, 𝄾 (eighth note, eighth rest)

400ms: ♩, 𝄽 (quarter note, quarter rest)

600ms: ♩. (dotted quarter note)

800ms: 𝅗𝅥 (half note)

The depiction of the rhythm is chosen so that each line stands for the signal being sent to a different finger. The upper line represents the thumb, the bottom line the pinkie, and each of the three lines in between represents the corresponding intermediate finger.

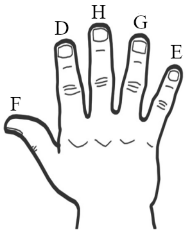

Figure 3.4: Each finger's correlation with the notes.

The rhythm is written in g major (thus the F sharp), to also sound harmonious when played as an auditory signal. The used audio file was edited so that when a note is played on the piano, no reverberations are heard after it is stopped from playing, and each note is exactly as long as specified.

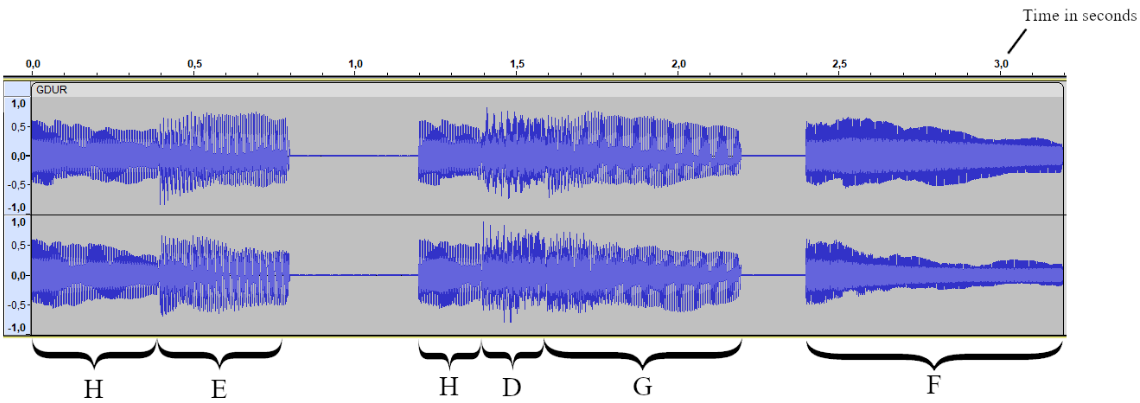

Figure 3.5: A view of the mp3 using Audacity [Aud].

When taking a closer look at the variables present in this study, we can distinguish between independent and dependent variables. The independent variables can be divided into two different groups:

The first one is the group a participant is part of and thus which signals he receives to learn the rhythm.
The second one is the tool used to play the rhythm, in this case, both a keyboard as well as a ukulele.

The dependent variable of this study will be the timing and duration of the notes and pauses played by the test subject.

3.4 Procedure

At the start of each session, the subject first got explained the idea behind the study. This means they were told about Passive Haptic Learning, got a short explanation of the findings made in previous studies, and got told that the goal of this study is to find out how different passive learning methods influence the reproduced rhythm.

It was especially important that the participants were told that it is not them who is getting tested, but how well the different learning strategies work. The functionality of the glove was also discussed to avoid any conscious or subconscious fear of the unknown wearable. Afterward, they had to sign an informed consent, stating they were informed of what they had to do in the study and were okay with their necessary data getting evaluated later. They were informed that they could cancel the session at any time, in case they felt unwell or stressed out.

The primary task that the subjects had to perform during the learning phase, was playing Tetris [Tet]. They were asked if they knew how to play and if that was not the case, a short explanation of the game was provided. Each subject also got an explanation of the game controls, having to use both hands on the keyboard to move and flip the Tetris pieces. Participants who had not played Tetris before were expected to reach a minimum score of 1000 points to count as "concentrated on the game". Experienced players were expected to reach a minimum score of at least 10000. The functionality of the glove and speakers was shortly tested for any malfunctions, then the learning phase began.

If the participant belonged to group *Hap* or *HapAud*, they were now told to put on the glove and start playing Tetris, and the 15-minute timer was started. No matter which group the participants belonged to, the game was muted so as not to obstruct the audio signals received in groups *HapAud* and *Aud*, or distract the player even further in group *Hap*. While the subject was playing Tetris, the glove sent tactile signals every 10 seconds, in case the participant was part of group *Hap*. In group *Aud* the auditory signal was also replayed every 10 seconds.
As found in "Simultaneous auditory and tactile information processing" [GeSR75], if auditory and tactile information is provided at the same time and the demand on cognitive processes is small, the stimuli can be processed as well as if only one type of stimuli is presented. If the demand on cognitive processes is greater, the simultaneous stimuli can be disruptive. To circumvent this, in group *HapAud* the test subjects also got sent haptic/auditory signals every 10 seconds, however, they were offset by a few seconds, so that the auditory signals played while there was a pause in between tactile signals and vice versa.

After 15 minutes were over, the subjects were told to stop playing and take the glove off, in case they had it on. During those 15 minutes, the rhythm was replayed via glove and/or audio exactly 68 times. The Tetris-Score of the participant was recorded to help conclude whether he was actually concentrating on the game or not. Afterward, the program used to track the timing and duration of key-presses on the keyboard was started and the participants were asked to reproduce the learned rhythm on the keyboard a total of three times. The subjects were free to use whatever keys and fingers they want but were encouraged to use two fingers to be able to replicate the 0ms-pauses in between notes. For each keypress, the exact point in time when the key was pressed and the duration were both tracked in milliseconds. When pressing a key on the keyboard the participant got no audio feedback.

After reproducing the rhythm on the keyboard, the subject was given a ukulele and got two minutes to familiarize himself with the instrument. The participant was asked to try to create and stop a sound to be able to properly stop a string from producing sounds when a pause is in between two notes. The participant was then asked to reproduce the learned rhythm on the ukulele three times. The test subject got told that they were free to use any strings of the ukulele they want, but were encouraged to avoid using several strings as that may lead to unwanted mistakes of mechanical nature. They were also asked to not let the last note of the rhythm fade out, but to stop it when it felt appropriate to reproduce the rhythm. An audio recording of the ukulele was used to evaluate the findings later. At the end of the session, a semi-structured interview was held, asking pre-written questions depending on the participant's group, as well as asking for any comments regarding the study.

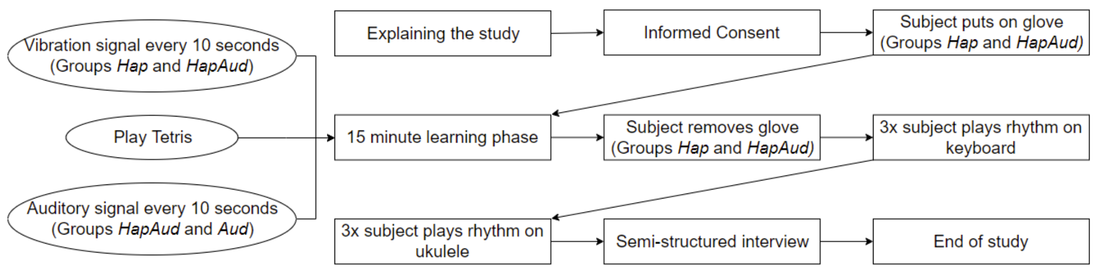

Figure 3.6: A simple overview of the procedure of the study.

3.5 Additional information regarding the study during the Covid-19 pandemic

As this study was conducted in early 2022, additional safety regulations had to be heeded in face of the Covid pandemic. Before each session of the study, all persons partaking had to test negative for Covid, as well as disinfect both hands before getting access to the glove, keyboard, or ukulele. During the learning phase as well as the rhythm-reproducing phase, the participants were free, but not obliged to wear a mask.

4. Evaluation

4.1 Recorded data

4.1.1 Data recorded from the keyboard

To track the exact milliseconds of when a key was pressed on the keyboard and for how long it was held, a program was written in C#, that uses the KeyPressEventHandler from the System.Windows.Forms namespace to record each key-press. The results are written into a txt-file and formatted to allow for easy evaluation.

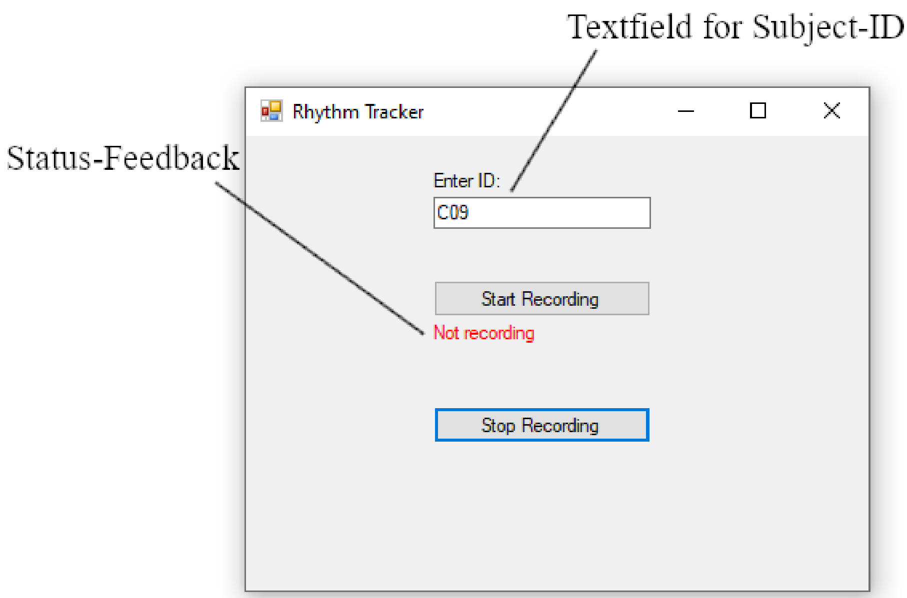

Figure 4.1: The UI of the program used to track the test subjects' inputs.

The first thing the participant was asked to do after starting the program was to input their ID, to later correctly match the data with him or her. After the test subject successfully inputted their ID, they were asked to click the "Start Recording" button and input the learned rhythm using any keys they want. Afterward, the user was to click the "Stop Recording" button and had a few seconds to relax. They were then asked to repeat the process two more times.

An example of the formatted data from a participant looks as follows:

Pressed from: 0 to 479
Pressed key 'L' for 479 milliseconds
Pause since previous note: 0

Pressed from: 440 to 855
Pressed key 'K' for 415 milliseconds
Pause since previous note: -39

Pressed from: 1299 to 1537
Pressed key 'L' for 238 milliseconds
Pause since previous note: 444

Pressed from: 1498 to 1733
Pressed key 'K' for 235 milliseconds
Pause since previous note: -39

Pressed from: 1701 to 2405
Pressed key 'L' for 704 milliseconds
Pause since previous note: -32

Pressed from: 2587 to 3483
Pressed key 'K' for 896 milliseconds
Pause since previous note: 182

Every three lines belong to a single keypress. The first line shows the exact moment in time since the first keypress of this recording session, that a key has been pressed down and then released. The value is given in milliseconds.
The second line shows how long the key has been held, as well as which key was used. This information can show if the user fat-fingered a button by accident, and lets us conclude how many fingers the participant was using in total when playing the rhythm. As mentioned before, the actual key pressed does not matter in this study.
The third line shows how long the test subject waited in between two keypresses in milliseconds. A negative number implies that the participant held two keys at the same time, while he was switching fingers.
Since the participant was asked to replicate the rhythm three times, two more keypress sequences are saved for each subject.

An example of a perfect replica of the original rhythm would be the following:

Pressed from: 0 to 400
Pressed key 'H' for 400 milliseconds
Pause since previous note: 0

Pressed from: 400 to 800
Pressed key 'E' for 400 milliseconds
Pause since previous note: 0

Pressed from: 1200 to 1400
Pressed key 'H' for 200 milliseconds
Pause since previous note: 400

Pressed from: 1400 to 1600
Pressed key 'D' for 200 milliseconds
Pause since previous note: 0

Pressed from: 1600 to 2200
Pressed key 'G' for 600 milliseconds
Pause since previous note: 0

Pressed from: 2400 to 3200
Pressed key 'F' for 800 milliseconds
Pause since previous note: 200

4.1.2 Data recorded from the ukulele

To evaluate the data recorded when the test subject was playing the ukulele, the program Audacity [Aud] was used.

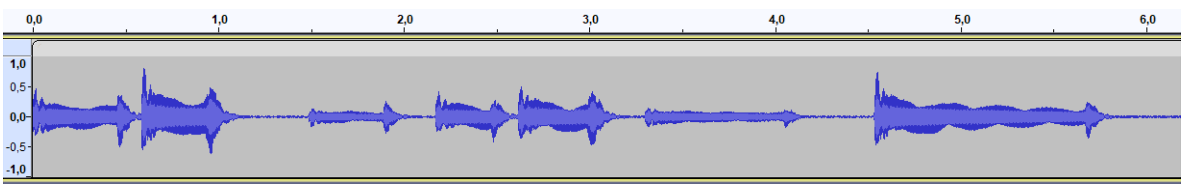

Figure 4.2: An example of how a sequence played by a participant is displayed in Audacity.

The spikes that can be seen at the end of some notes, see Figure 4.4, result from the participant putting his finger on the swinging string in order to stop the sound.

This leads to an approximately 100 milliseconds long additional sound that was not intended by the participant. Thus I will not be including the spike when recording how long a note has been played for, and instead count it towards the pause in between two notes.

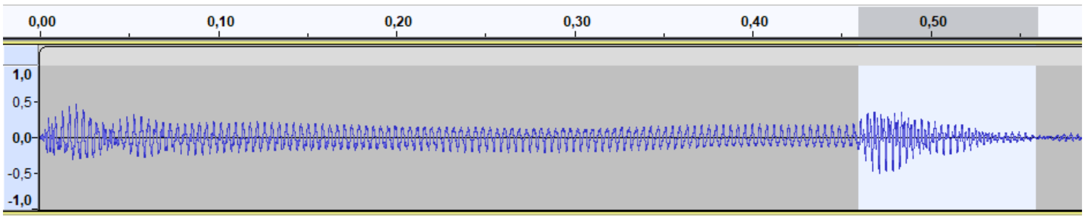

Figure 4.3: An example of a single note as seen in Audacity. The highlighted part represents the part of the note that the test subject did not want to play since his finger touched the string in order to stop it.

When trying to pinpoint the exact moment in time, that the participant stopped the string from swinging freely or started playing a different note, Audacity allows for a Zoom-In that clearly shows the change in oscillations and the milliseconds the note lasted since it was played. An error of around +/- five milliseconds has to be considered, but it is small enough to not matter in the overall results.

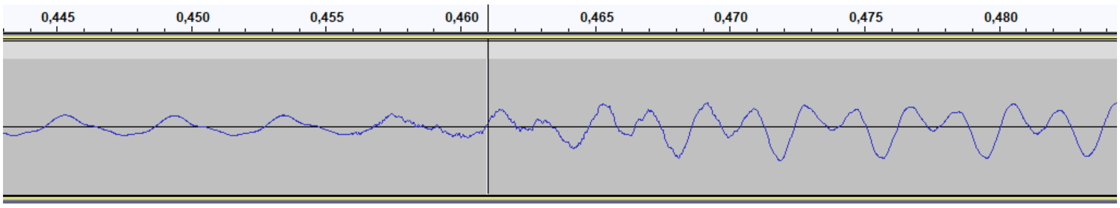

Figure 4.4: A close up showing the exact moment the note changes from swinging unhindered (left of black line) to being obstructed by the participants finger (right of black line). The length of the note in this case would be considered to be 461 milliseconds.

Participants who had played the ukulele or other string instruments before would sometimes be skilled enough to stop a string from playing a sound when stopping it. In those cases, no corrections had to be made and the full duration of the sound was taken into account.

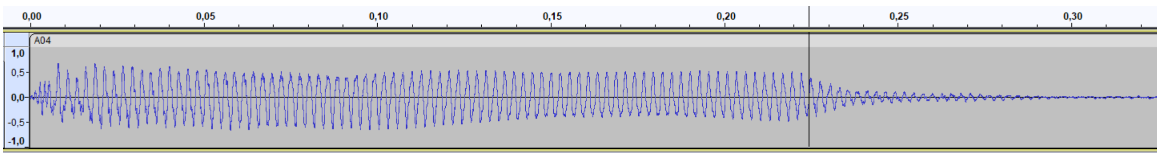

Figure 4.5: A close-up of a note played by an experienced guitar player. There is no spike in amplitude, instead, a quick decline can be seen. The note is considered to be ”stopped” by the participant at the beginning of the amplitude reduction, marked here by the black line.

To make pauses of zero milliseconds achievable when playing the ukulele and using only one string pauses of under 100 milliseconds were considered to be non-existent. This was done in order to compensate for the time, the finger of a participant had to rest on the string in order to play a new sound.

If the rhythm would have been performed perfectly on the ukulele, the resulting Audacity-view should look similar to Figure 3.5, with the exception of possible spikes after notes ”E” and ”G”.

4.2 Dynamic Time Warping

The Dynamic Time Warping (DTW) algorithm is very well-known and is used in a lot of different fields. It is efficient in measuring time-series similarity by allowing ”elastic” transformation of time series [Seni08] and finding the optimal global alignment between them. This can for example be used in recognizing human speech [PeHP19] or gestures [RPRV17]. In algorithm 1 the pseudo-code for the distance-function of the DTW algorithm is shown.

Algorithm 1 CalculateDTWDistance(PlayedRhythm, OriginalRhythm)

```
s ← PlayedRhythm.length
t ← OriginalRhythm.length
DTW ← array[0..s, 0..t]
DTW[0, 0] ← 0
for i := 1 to s do
    for j := 1 to t do
        DTW[i, j] ← infinity
    end for
end for
for i := 1 to s do
    for j := 1 to t do
        cost ← |PlayedRhythm[i − 1] − OriginalRhythm[j − 1]|
        DTW[i, j] ← cost+MIN(DTW[i−1, j], DTW[i, j−1], DTW[i−1, j−1])
    end for
end for
return DTW[s, t]
```

In literature, the cost is often calculated using a non-specified distance function, in this case, it is implicitly exchanged for the function |a-b|, as the absolute difference in duration of a note or pause dictates how ”correct” it is. To calculate the actual distance, the newly calculated cost between two single notes has to be added to the minimum distance calculated up to that point.

The variable ”DTW” refers to the distance matrix of the two rhythms. It is used to track the distance between parts of the played and original sequences, with the last value of the matrix containing the distance between both full rhythms. This is the value used to measure the error of the played rhythm.

In addition to being very quick, the Dynamic Time Warping algorithm also allows for the two sequences to be of different lengths, meaning the test subject can play additional notes or play less than in the original rhythm. Without the algorithm, it would have been near impossible to match the additional / missing notes with the original. For example, if the test subject played the rhythm flawlessly, except missing the second original note, if every note and pause would be matched in order, a huge error would be amassed when summed up.
Instead, the DTW algorithm can detect that the actually made mistake is relatively small and the resulting error would be accordingly small.

The first ones to use the Dynamic Time Warping algorithm to calculate the error between two rhythms were Huang et al. in their study "Mobile Music Touch" [HSDW+10]. They compared the results between two groups, one having learned the rhythm passively via audio and tactile signals, the other one only having audible signals. They used the same distance function as in this study.

4.3 Evaluation of Duration

To evaluate the results, different aspects of the rhythm played by the participants have to be taken into account. We will first be analyzing the correctness of duration regarding both notes and pauses played.

4.3.1 Comparison in between groups

As can be seen in the algorithm 1, the function only uses two arrays to calculate the DTW-distance. The first array "PlayedRhythm" refers to an array containing the time-data of the subjects played note sequence. The "OriginalRhythm" refers to the rhythm written for this study. The format of those arrays is as follows:

$$[Note, Pause, Note, Pause, ..., Note]$$

A *note* refers to the duration in milliseconds a note has been played by the participant, *pause* to the duration the test subject waited in between two notes. As seen in section 4.1.1, pauses can also be negative values. The original rhythms format would thus be:

$$[400, 0, 400, 400, 200, 0, 200, 0, 600, 200, 800]$$

To evaluate the data, a two-factor ANOVA, using the DTW error of each try performed by the participants as data and the different groups and instruments as the considered factors was used.
A statistically significant difference in average performance by both group division as well as instrument-choice could be found. Using an alpha-value of 0.05 for the error rate, we found a P-value of 0.00017 as well as an F-value of 15.36 which is well above the critical F-value of 3.94 for the significance of the instrument. When taking a look at the group division, we get a P-value of 0.00007, an F-value of 17.23, and a critical F-value of 3.94. Once again the calculated F-value is larger than the critical value, making the difference in instruments statistically significant.

When analyzing the combination of both group division and instruments, a P-value of 0.01225, F-value of 6.52, and critical F-value of 3.94 is calculated. This means that for the duration of notes and pauses played by participants, the interaction of both factors is of statistical significance.

When taking a look at the average DTW error of each of the groups we get the following results:

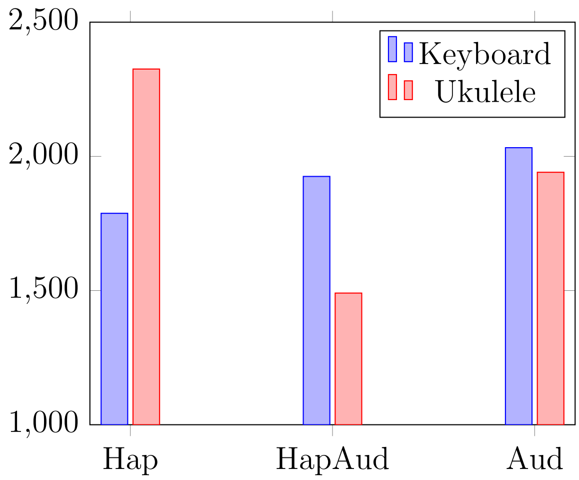

Figure 4.6: Bar chart showing the average DTW error regarding the correctness of duration per group.

When comparing the results regarding the average Dynamic Time Warping error of the rhythm played on the keyboard, only slight differences can be seen. Group *Hap* performed the best, with an average error of 1788. Having only received haptic signals, the participants could only rely on the haptic feedback felt when pressing a key on the keyboard to match the played rhythm with the one felt during the learning phase. Since they had not heard the rhythm before, there was no ”unnecessary” information memorized to influence the recreation of the rhythm.

Group *HapAud* performed slightly worse than group *Hap*, having an average error of 1925. The difference in performance can be explained through multiple reasons. The first one would be a statistical blur, meaning that group *Hap* and *HapAud* are expected to perform the same, but since the number of participants per group is limited, small inaccuracies are to be expected. Since the participants in each group also have different amounts of musical experience and could only be roughly matched with each other, some more noise in the data is unavoidable.
Another reason explaining the difference is a cognitive overload, as mentioned in ”Simultaneous auditory and tactile information processing” [GeSR75]. As mentioned in section 3.4, a delay in between the haptic and audio signals was used for group *HapAud* to try and negate the disruption caused by having both types of signals received by the participant, however, the delay might be too short to fully allow that. Further research would be necessary to confirm these findings.

The group performing the worst overall on the keyboard is group *Aud* with an average error of 2032. This could once again be explained by statistical blur as done

for group *HapAud*.
Another explanation of the result is a lack of ”muscle memory”, that the other two groups had when playing the rhythm on the keyboard. Since group *Aud* only had audio information about the rhythm and the keyboard provided no audible feedback, group *Aud* could not match the haptic feedback felt in their finger when pressing a key with any memorized signal from the learning phase.

Comparing the Dynamic Time Warping errors of the rhythms played on a ukulele, bigger differences than for the keyboard can be seen. Group *Hap* performed the worst of the three groups, having an average error of 2325. Having never heard the rhythm unlike the other groups and only receiving audible feedback when playing the ukulele, once again shows the mismatch of learned signal vs. feedback received when playing the rhythm, as group *Aud* did when playing on the keyboard.

Group *Aud* performed better than group *Hap*, having an average error of 1941. Since the ukulele mainly provides audible feedback, the participants were able to properly match the played rhythm with the original one they heard before.

The group performing the best was group *HapAud* with an average error of 1491. The difference to the error of group *Hap* was expected since, like group *Aud*, the audible feedback of the ukulele could be matched with the memorized audible rhythm. However in this case the additional haptic signals received in the learning phase seem to greatly improve the performance of the participant when playing the rhythm on an instrument that is unable to fully utilize the muscle memory obtained during the learning phase.

4.3.2 Comparison within a group

When calculating the average DTW error of each participant in group *Hap* we get the following results:

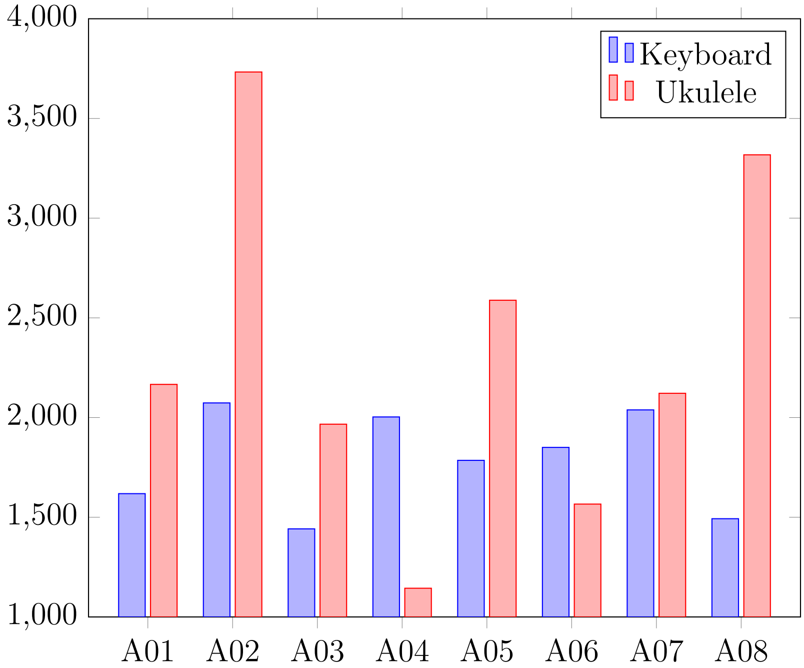

Figure 4.7: Bar chart showing the average DTW error regarding the duration of the rhythm in group *Hap*.

To evaluate the data, a two-tail t-test assuming unequal variances was performed, using the DTW error of each participant's try per instrument as data. Like in the Anova analysis we use an alpha value of 0.05. The calculated P-value is 0.00687, meaning that the difference in instruments is of statistical significance.

Six out of eight test subjects performed better when playing the rhythm on the keyboard, rather than on the ukulele. This seems to suggest that Passive Haptic Learning is the best way to learn a rhythm when it is applied to an instrument, where a haptic signal can easily be translated into a simple movement. In this case, a vibration directly matches with the down-movement of a finger when pressing a key.
The difference in errors between keyboard and ukulele visualizes the mismatch of haptic learning and the application of the learned action in a new context. Here, matching a single felt vibration with two different types of finger movement (strumming and stopping a string) seems to be more difficult for the participants.

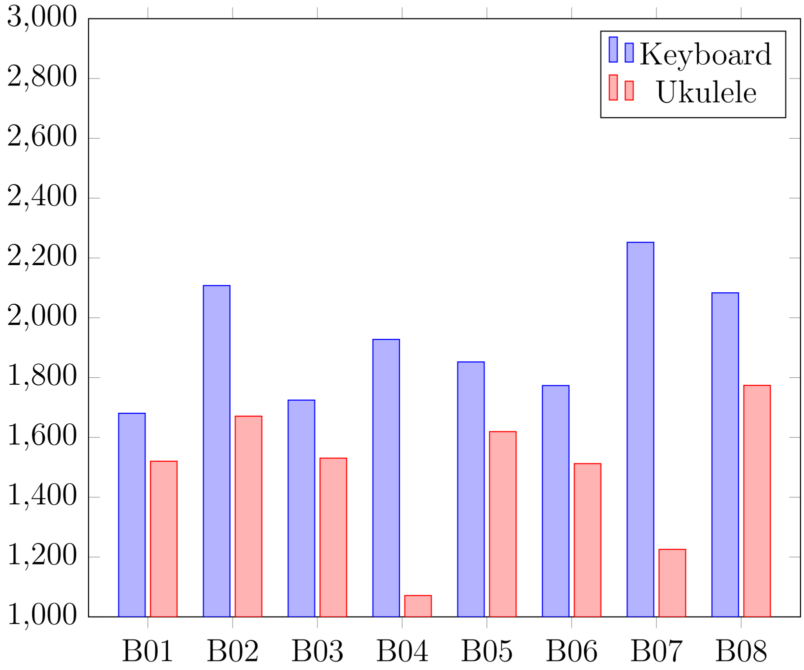

Figure 4.8: Bar chart showing the average DTW error regarding the duration of the rhythm in group *HapAud*.

Like for group *Hap*, we will use the same t-test to evaluate the statistical significance of the difference in instruments. For group *HapAud* we get a P-value of 0.000001, once again confirming that the different instruments heavily impact the participants performance.

Looking at the results of group *HapAud*, all participants performed better when playing the rhythm on the ukulele. Those findings suggest that the auditory feedback received when playing an instrument is of great advantage when having received both audible and haptic signals during the learning phase.
It can be argued that the audio signals from the learning phase are of greater importance, as the difference between having no audio signals vs. having them is greater than no haptic signals vs. haptic signals. It should still be noted that the difference the haptic signals make, is by no means insignificant, as can be seen when comparing groups *HapAud* and *Aud*.

Another aspect to consider is that the introduction of haptic signals in addition to auditory signals affects the participant's performance regarding the ukulele more than the keyboard. This phenomenon is unexpected as the results from group *Hap* show that haptic signals themselves make playing the rhythm on a keyboard easier than on the ukulele. A possible explanation is that the additional haptic signals are simply adding extra information to the participant's memory, improving his overall performance, however the lack of audible feedback from playing the rhythm on the keyboard caps the effect of the additional information.

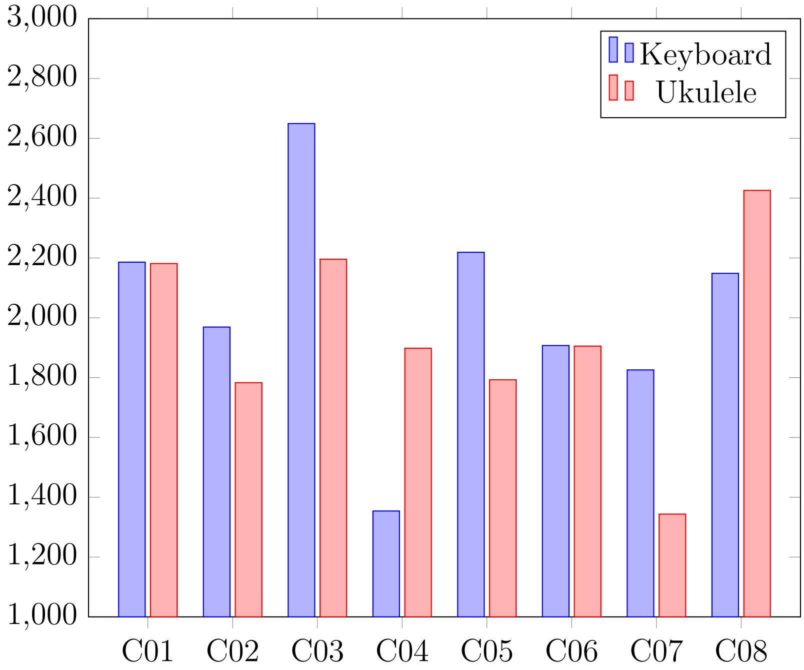

Figure 4.9: Bar chart showing the average DTW error regarding the duration of the rhythm in group *Aud*.

For group *Aud*, the t-test gives us a P-value of 0.39921, making the difference of instrument for this group insignificant.

In group *Aud*, four out of eight people performed significantly better when playing the rhythm on the ukulele rather than the keyboard. Two of the remaining participants performed better on the keyboard, while the last two had similar results when using either the ukulele or keyboard. Together with the analysis of the t-test, this suggests that the movement performed to play the instrument is of little to no importance when only auditory signals were given during the learning phase.

4.3.3 Evaluating consistency

An interesting aspect of the learned rhythm is whether or not the participants were able to replay the rhythm they memorized consistently, or if they made great changes in between the three attempts they were given for each instrument. To evaluate the consistency of the played rhythms, the Dynamic Time Warping algorithm is used once more.
Since the original rhythm is irrelevant when checking whether the played rhythm is consistent in between several tries, the DTW algorithm now uses user data for both input arrays as seen in algorithm 1. For each participant, the algorithm ran six times, calculating the DTW distance between try 1 and 2, try 2 and 3 as well as between try 1 and 3 for both the keyboard and ukulele respectively. Lastly, the distance was averaged for each instrument.

To evaluate the data, we will once again use a two-factor Anova to check if the data is statistically significant.
The critical F-value for group division, instruments as well as their combination

is 4.196. When looking at the significance of instruments, we get a P-value of 0.06892 and an F-value of only 3.58, making the difference between instruments non-significant. For the group division, a P-value of 0.69727 and an F-value of 0.15 are achieved. Once again, no statistical significance could be determined. The combination of both factors yields similar results with a P-value of 0.79306 and an F-value of 0.07.

We can conclude that the type of signals received during the learning phase does not influence how consistently the participant is able to recall the memorized rhythm. As no statistical significance could be found for any factor, no further analysis will be done for the consistency of duration.

4.4 Evaluation of Timing

Since the duration of notes and pauses is not the only important aspect of rhythms, the timing of single notes in relation to the first one will also be further analyzed.

The evaluation of timing will give insight into the ability of the participants to keep track of the pulse of the rhythm since the duration-analysis would show large errors if the participants timed every note perfectly, but played a note for too long or short.

4.4.1 Comparison in between groups

To find a fitting format for the arrays which will be inserted in the Dynamic Time Warping algorithm, the exact milliseconds since the first creation of a sound per rhythm will be used for each note. The pauses of the rhythm will be implicitly present in the data since they were added to the duration of the notes in order to get the timing of a note.
The originals rhythms format is thus:

$$[0, 400, 1200, 1400, 1600, 2400]$$

To evaluate the data, we once again use a two-factor ANOVA, using the DTW errors of each try as data and the different groups and instruments as factors.
A statistically significant difference in average performance by instrument choice could be determined. Like in the evaluation of duration, an alpha-value of 0.05 was used for the error rate. We found a P-value of 0.01663 as well as an F-value of 5.95 which is above the critical F-value of 3.94. When taking a look at the group division, we get a P-value of 0.16451, an F-value of 1.96, and a critical F-value of 3.94. Since the calculated F-value is smaller than the critical value, the division of groups is statistically-insignificant to the performance of the participants.
When analyzing the combination of both group division and instruments, a P-value of 0.78067, F-value of 0.08, and critical F-value of 3.94 is calculated. This means that for the timing of notes played by participants, the interaction of both factors is of no significance.

When taking a look at the average DTW error of each of the groups we get the following results:

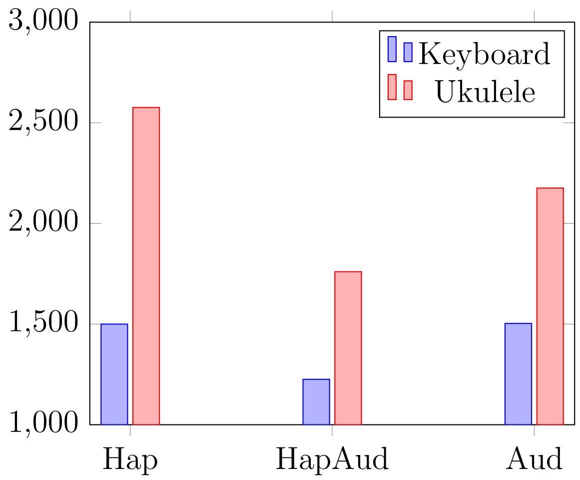

Figure 4.10: Bar chart showing the average DTW error regarding the correctness of timing per group.

When comparing the results of timing data, it becomes apparent that, unlike the duration errors, each group performed significantly better when playing the rhythm on the keyboard, not the ukulele. It is likely that playing the ukulele or string instruments in general, was very unfamiliar for most participants. This means that they had to use most of their concentration on the strumming and stopping of a string, and could not properly time their notes.

Getting the timing on the keyboard right is considered a much easier task, as the movement of the finger requires less attention from the participant, meaning it was easier to concentrate on the recreation of the original rhythm.
As the Anova analysis showed, the differences seen between groups are of no significance.

4.4.2 Comparison within a group

When calculating the average DTW error of each participant in group *Hap* we get the following results:

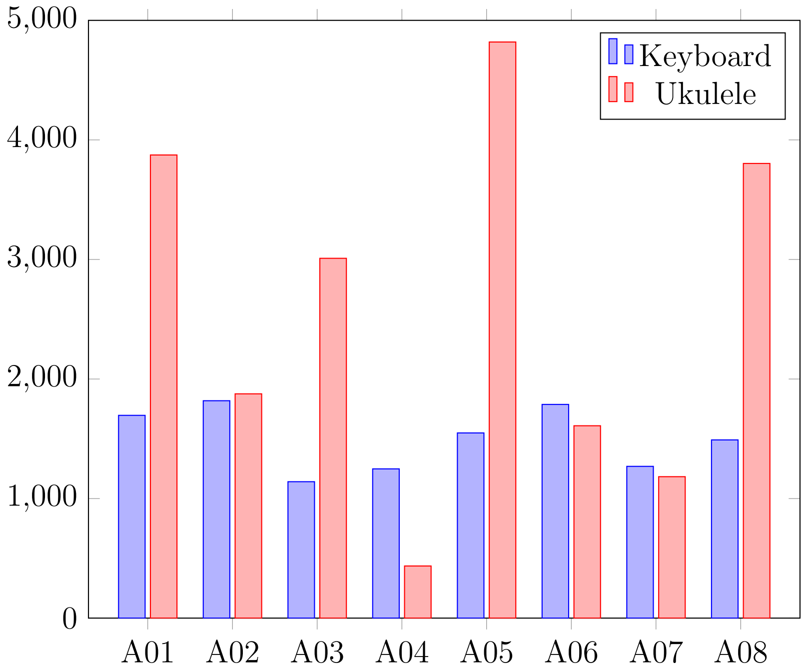

Figure 4.11: Bar chart showing the average DTW error regarding the timing of the rhythm in group *Hap*.

We will once again try to confirm the hypothesis, that the difference in instruments is of statistical significance within a group. To evaluate the data, we will use the same t-test used for the within-group evaluation of duration. Group *Hap* achieves a P-value of 0.00243, meaning that the hypothesis is confirmed.

Four out of eight people performed significantly worse when playing the rhythm on the ukulele compared to the keyboard. Three participants showed similar results on both instruments, while one test subject showed better results on the ukulele. Overall the performance was better on the keyboard, showing that the haptic signals help more with the instrument that gives haptic feedback, as also seen in the evaluation of duration.

The timing error on the keyboard is relatively consistent for all participants, while the error from the ukulele is strongly varying. A possible explanation would be the unfamiliarity and difficulty of the instrument, as discussed in the previous section. Another explanation is that some test subjects were thrown off by the audio feedback of the ukulele since they had never heard the rhythm before and thus were more likely to lose track of the rhythm they were playing.

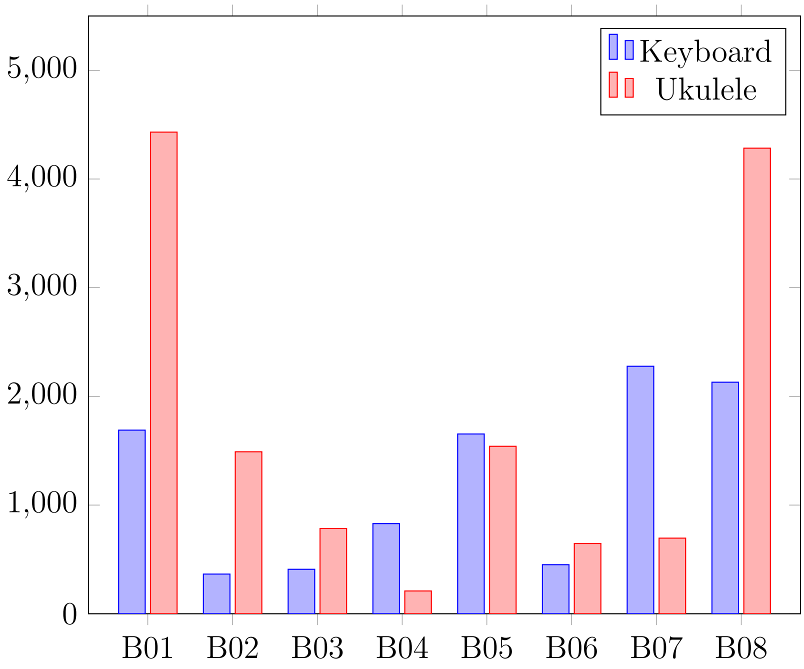

Figure 4.12: Bar chart showing the average DTW error regarding the timing of the rhythm in group *HapAud*.

When using the t-test to calculate the P-value for group *HapAud*, we get a value of 0.17549. This means that we accept the null-hypothesis: The difference in instruments is non-significant when having received both auditory and haptic signals in the learning phase.

In group *HapAud* four out of eight people performed better when playing the rhythm on the keyboard rather than the ukulele. Two participants had similar results on both instruments, the remaining two test subjects performed better on the ukulele. In addition to the t-test, this visually confirms the insignificance of the instrument once again.

Unlike in group *Hap*, only two participants had an error exceeding 2000 on the ukulele, instead of four. As group *HapAud* had audio signals available during the learning phase, the explanation of unfamiliarity with a ukulele seems more plausible to explain the spikes in errors.

Another difference to group *Hap* is the increasing variance in errors regarding the keyboard. While in group *Hap*, most keyboard performances could be considered "mediocre", in group *HapAud* three participants got near-perfect timing results on the keyboard, while two others got errors exceeding 2000. This seems to suggest, that some participants were able to use the additional audio information from the learning phase to their advantage, while others were unable to use it and instead performed worse than test subjects with only one type of signal.

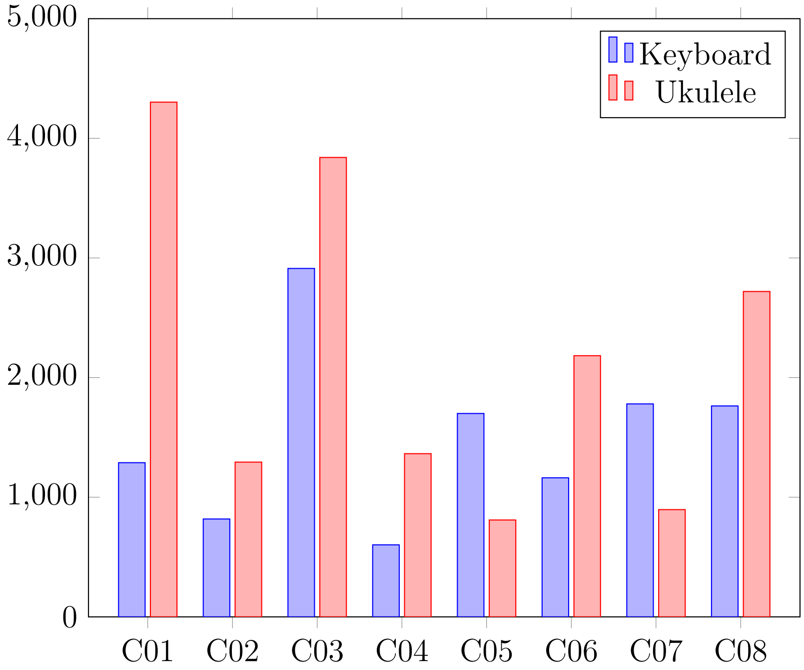

Figure 4.13: Bar chart showing the average DTW error regarding the timing of the rhythm in group *Aud*.

In group *Aud* the P-value calculated with the t-test is 0.03599, meaning that the difference in instruments is statistically significant.

Six out of eight participants in group *Aud* performed better when playing the rhythm on the keyboard rather than the ukulele, the other two conversely. This shows that regarding timing, the keyboard is overall considered as the instrument which produces more satisfying performances.
Like in group *Hap*, four people exceed the error value of 2000 when playing on the ukulele, further confirming that those errors are not because of the audio feedback received when playing the ukulele, but instead, unfamiliarity with the instrument.

Like in group *HapAud* the variance of keyboard errors is larger than in group *Hap*. This indicates that audio signals received in the learning phase can influence the results of the participant either positively or negatively, while haptic signals alone allow for a more consistent performance.

4.4.3 Evaluating consistency

As done for the evaluation of duration, the consistency of timings will be calculated in a similar manner. To evaluate the data, we will use the two-factor Anova to check if the data is statistically significant.
The critical F-value for group division, instruments as well as their combination is 4.196. When looking at the significance of instruments, we get a P-value of 0.91447 and an F-value of only 0.01, making the difference between instruments non-significant. For the group division, a P-value of 0.49066 and an F-value of 0.49 are achieved. Once again, no statistical significance could be determined. The combination of both factors yields similar results with a P-value of 0.54903 and an

F-value of 0.37.

As no statistical significance could be found for any factor, no further analysis will be done for the consistency of timing.

4.5 Evaluating feedback

After a participant finished playing the rhythm on the keyboard and ukulele, a semi-structured interview was conducted, where each participant got asked questions fitting the group they belonged to as well as getting asked for any kind of comments about the study.

Participants from group *Hap* and *HapAud* were asked to rate the comfortability of the glove between 1 (very uncomfortable) and 5 (very comfortable). The average score was 4.0625, with the main complaint being that the glove was too heavy for comfort.

Each group got asked how well they thought they did on the different instruments. They once again were asked to rate their own performance between 1 (very poor) and 5 (perfect replica of the original rhythm). Group *Hap* perceived themselves as being the worst with a score of 2.9, group *HapAud* the best with a score of 3,6, and group *Aud* in the middle with a score of 3. These scores resemble the average data evaluated for both the duration of notes and pauses as well as the timing of notes, with group *Hap* performing the worst and group *HapAud* the best.

Participants also were to rate how much attention they paid to the different signals they received during the learning phase, once again between 1 (no attention at all) and 5 (concentrated on signals instead of the game). No participant gave a number higher than three. According to the feedback, the glove was easier to ignore, with an average score of 2.1 in group *Hap* and 1.5 in group *HapAud*. The audio signals were considered more intrusive, with an average score of 2.3 in both group *HapAud* and *Aud*.

Group *HapAud* was further asked if they thought the audio or haptic signals to be more useful. Seven out of eight people named the audio signals to be more effective for learning the rhythm, although the gathered data seems to indicate that the additional haptic signals have a significant impact on the performance of the participants.

When asked for any kind of additional comments, two stuck out in particular. The first one is from a participant of group *Hap*: Since the rhythm was never heard by the test subject, they were reminded of a previously known rhythm by the haptic signals and kept recalling that one in their mind. This shows the danger of using haptic signals alone as they might get mixed up with already memorized rhythms in the participant's mind and lead to wrong results.

Another comment mentioned how the participant was already very familiar with the game of Tetris, making it possible to formulate complex strategies for the game and having no time at all to concentrate on the glove. This makes it feasible to use tasks well known to participants in future studies, where they are still required to use all their concentration on performing the primary task, instead of first having to learn the primary task as well.

5. Conclusion and Future Work

5.1 Conclusion

This study investigated how haptic and auditory signals influence the ability to recreate a passively learned rhythm. In addition, two different types of tools were used by the test subjects to play said rhythm, a keyboard, and a ukulele. While the performance of the participants showed only small differences in regard to the keyboard, large disparities could be found in the results calculated from the data concerning the ukulele.

It was found that the ability of the participants to recreate the duration of notes and pauses on the ukulele was by far the best when having both haptic and auditory signals during the learning phase. From this, we can conclude that having both muscle memory as well as a melody to recall in one's head leads to the best results. Furthermore, we found that using haptic signals alone seems to be the worst choice to teach rhythms for instruments that require more complex actions to play than pressing a key. This is likely due to the mismatch between the type of received signal (haptic) and received feedback during the recreation of the rhythm (auditory).

Regarding the timing of the notes within the rhythm, we found a significant difference in results between the keyboard and ukulele. Each group performed notably better on the keyboard, which we concluded, is attributable to the unfamiliarity of the ukulele as well as the more complex motion required to play it.

Furthermore, the average recall consistency of all groups was evaluated, showing that in regards to both duration and timing, no statistical significance could be found for either the difference in groups or instruments.

5.2 Outlook

For future work, several things can be considered. Since this study was the first to compare the effects of Passive Haptic Learning in the context of multiple instruments, more work would be required to confirm and expand the findings made here.

An investigation of the ability to play a passively learned rhythm on even more different kinds of instruments would surely yield surprising and interesting results, that could revolutionize the way music and instruments are studied by both beginners as well as experienced musicians.

Another area of further research would be how different kind of feedback received during the recreation of a rhythm influences the results. In this study, the instruments differed in both the motion required to play it as well as the type of feedback received, auditory in the case of the ukulele and haptic in the case of the keyboard. A further partition into multiple feedback groups would yield more detailed and conclusive data.

Another interesting variable affecting the results of the played rhythm is the musical experience that participants had before taking part in the study. It is imaginable that previous experiences with learning rhythms could affect the performance of the participants positively, making it easier to understand certain patterns. However, it could also make it more difficult, since the participants might have expectations regarding the rhythm and be prejudiced against certain patterns which would allow for more mistakes during the recreation.

Investigating the retention in Passive Haptic Learning of rhythms as already done for the pressing of piano keys in the correct order [DoPB21] could also lead to new insights.

A. Appendix

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
A01	Try 1	337	299	297	690	170	145	181	174	215	582	514
	Try 2	338	283	367	524	147	98	145	96	179	622	786
	Try 3	319	287	301	567	158	141	160	146	219	526	879
A02	Try 1	380	598	352	696	459						
	Try 2	364	690	427	710	667						
	Try 3	238	639	381	583	520						
A03	Try 1	278	237	512	439	170	116	928	360	781		
	Try 2	238	243	582	380	140	176	754	345	655		
	Try 3	268	275	634	311	143	145	929	200	748		
A04	Try 1	255	276	270	735	100	118	100	121	150	485	667
	Try 2	173	313	290	802	99	105	102	110	124	446	505
	Try 3	213	246	301	771	99	104	116	82	149	353	750
A05	Try 1	292	227	276	592	206	71	194	86	379	355	228
	Try 2	302	316	233	647	180	136	196	97	203	591	240
	Try 3	374	240	374	693	222	76	215	107	208	457	191
A06	Try 1	200	391	118	149	197	289	166				
	Try 2	216	477	121	153	165	334	164				
	Try 3	162	432	102	166	144	371	126				
A07	Try 1	469	756	188	344	97	494	94	231	83	252	90
	Try 2	524	188	288	167	138	392	89	229	102	222	106
	Try 3	436	254	387	162	237	298	38	304	102	234	118
A08	Try 1	268	353	846	171	548	82	898				
	Try 2	360	246	637	541	340	242	656				
	Try 3	385	227	812	552	541	144	918				

Table A.1: Keyboard rhythm data of Group *Hap* (Haptic Signals only) in milliseconds.

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
A01	Try 1	657	260	685	583	380	0	355	0	293	373	1039
	Try 2	704	305	807	457	339	0	377	0	388	418	1395
	Try 3	734	284	911	421	413	0	372	0	349	371	1043
A02	Try 1	515	490	444	776	1816						
	Try 2	417	484	352	668	2017						
	Try 3	403	562	377	593	2352						
A03	Try 1	302	134	507	695	281	0	569	592	683		
	Try 2	338	236	576	696	355	0	660	848	1107		
	Try 3	390	192	1008	623	377	0	1071	641	1187		
A04	Try 1	302	202	289	451	256	0	239	0	240	352	622
	Try 2	236	245	371	502	248	0	214	0	265	350	709
	Try 3	267	151	393	443	232	0	225	0	258	378	704
A05	Try 1	372	329	263	1216	234	539	249	173	330	405	380
	Try 2	310	374	257	1352	368	0	242	214	463	507	336
	Try 3	274	515	363	995	365	0	245	247	499	489	371
A06	Try 1	213	445	252	0	237	403	364				
	Try 2	257	474	233	0	329	344	461				
	Try 3	230	571	287	0	363	419	677				
A07	Try 1	253	463	281	272	322	292	135	228	145	225	181
	Try 2	242	503	224	361	235	329	152	142	163	217	189
	Try 3	282	469	267	306	261	246	199	206	166	213	154
A08	Try 1	507	410	1266	696	649	306	1013				
	Try 2	591	427	1026	870	922	373	403				
	Try 3	603	416	1174	786	640	437	208				

Table A.2: Ukulele rhythm data of Group *Hap* (Haptic Signals only) in milliseconds.

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
B01	Try 1	356	182	281	540	288	7	159	155	320	394	244	102	623
	Try 2	254	201	203	498	163	64	196	98	413	214	367	157	419
	Try 3	313	337	259	649	150	32	125	167	387	469	272	159	486
B02	Try 1	348	66	134	577	117	69	102	110	100	661	64		
	Try 2	202	266	136	569	128	78	112	110	121	684	88		
	Try 3	88	256	116	604	124	61	122	100	112	657	119		
B03	Try 1	166	229	405	268	116	87	127	96	147	545	243		
	Try 2	173	222	354	410	103	77	103	105	211	567	432		
	Try 3	147	270	335	380	96	90	111	96	138	573	188		
B04	Try 1	208	220	569	311	97	93	96	125	483	410	502		
	Try 2	210	198	634	231	73	98	87	135	435	374	441		
	Try 3	181	192	458	377	78	95	81	165	446	297	516		
B05	Try 1	148	111	161	469	163	758	147						
	Try 2	149	91	172	493	182	753	251						
	Try 3	155	100	187	528	204	683	185						
B06	Try 1	203	175	207	576	142	26	110	96	204	510	657		
	Try 2	171	189	167	586	148	34	158	103	149	586	459		
	Try 3	162	180	183	543	187	6	137	91	158	572	474		
B07	Try 1	233	385	148	1114	126	140	129	148	116	510	145	334	235
	Try 2	185	267	128	882	101	154	157	108	47	783	158	259	353
	Try 3	201	243	169	639	130	92	212	86	136	669	132	273	404
B08	Try 1	110	303	650	354	107	143	95	179	698	498	989		
	Try 2	188	333	801	299	111	139	83	166	870	455	697		
	Try 3	180	365	767	340	101	144	75	227	1020	474	1171		

Table A.3: Keyboard rhythm data of Group *HapAud* (Audio and Haptic Signals) in milliseconds.

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
B01	Try 1	418	180	381	663	280	0	250	0	384	745	443	132	537
	Try 2	573	0	703	541	291	0	246	0	1026	190	445	157	1044
	Try 3	612	0	759	447	271	0	273	0	684	569	607	0	1096
B02	Try 1	594	0	797	0	301	0	176	0	624	404	957		
	Try 2	484	0	803	0	136	0	144	0	233	0	563	311	423
	Try 3	220	519	362	669	168	0	259	0	484	528	1298		
B03	Try 1	447	442	243	0	265	0	469	473	431				
	Try 2	454	479	265	0	226	0	452	529	486				
	Try 3	448	505	236	0	258	0	389	539	443				
B04	Try 1	393	0	295	407	226	0	218	0	287	422	286		
	Try 2	392	0	361	402	247	0	233	0	327	421	376		
	Try 3	393	0	389	370	197	0	254	0	398	390	342		
B05	Try 1	259	0	351	234	248	566	224						
	Try 2	249	0	314	293	200	609	204						
	Try 3	220	0	672	0	295	432	249						
B06	Try 1	398	0	396	0	354	407	433	404	488				
	Try 2	389	0	394	0	407	404	422	387	452				
	Try 3	381	0	388	0	395	423	387	385	417				
B07	Try 1	385	0	361	354	271	0	258	0	349	367	432	0	1043
	Try 2	416	0	377	284	216	0	295	0	427	238	421	0	794
	Try 3	511	0	257	441	240	0	294	0	266	423	427	0	585
B08	Try 1	389	410	583	765	404	0	287	231	639	364	613		
	Try 2	662	0	676	683	365	0	407	0	877	782	845		
	Try 3	448	326	904	333	357	0	425	0	989	481	834		

Table A.4: Ukulele rhythm data of Group *HapAud* (Audio and Haptic Signals) in milliseconds.

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
C01	Try 1	160	325	138	615	119	83	87	170	127	333	143	598	226		
	Try 2	137	183	141	509	103	80	110	152	129	420	127	219	140	641	122
	Try 3	153	228	381	413	135	107	115	130	103	234	126	260	133	693	146
C02	Try 1	308	255	232	792	88	98	92	93	66	383	179				
	Try 2	199	209	210	422	78	125	69	92	72	467	163				
	Try 3	191	264	253	479	81	148	85	99	54	519	363				
C03	Try 1	116	620	110	1275	101	136	85	263	89	617	120				
	Try 2	104	581	108	1168	92	177	74	256	83	564	156				
	Try 3	136	530	110	1078	101	148	84	262	85	593	155				
C04	Try 1	379	-23	731	163	178	-25	237	-14	449	-39	704				
	Try 2	286	86	329	615	154	0	146	20	296	46	635				
	Try 3	273	132	194	814	181	3	180	9	361	26	506				
C05	Try 1	134	184	99	361	75	114	96	169	163	328	99				
	Try 2	140	167	113	330	88	111	111	91	109	320	127				
	Try 3	134	188	114	334	99	107	115	105	113	322	121				
C06	Try 1	177	436	130	877	89	149	85	199	125						
	Try 2	117	434	577	357	106	172	87	205	1085						
	Try 3	112	379	747	305	108	186	89	199	1280						
C07	Try 1	316	396	128	75	135	108	245	345	254						
	Try 2	184	398	124	98	120	100	132	334	222						
	Try 3	182	384	96	120	124	120	131	328	134						
C08	Try 1	203	579	186	699	113	129	91								
	Try 2	174	539	184	727	192	86	162								
	Try 3	192	637	258	706	138	84	123	864	169						

Table A.5: Keyboard rhythm data of Group *Aud* (Audio Signals only) in milliseconds.

		Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note	Pause	Note
C01	Try 1	461	130	351	551	402	279	300	145	374	310	749	485	1137
	Try 2	415	163	471	789	445	178	259	308	591	672	1211		
	Try 3	344	262	816	966	308	285	677	461	751				
C02	Try 1	367	0	598	101	228	0	197	0	435	0	1791		
	Try 2	289	105	457	0	226	0	206	0	384	0	1440		
	Try 3	401	0	388	0	218	0	171	0	398	0	1942		
C03	Try 1	297	395	328	901	335	0	297	0	364	304	353		
	Try 2	487	448	326	1132	324	0	337	0	298	388	473		
	Try 3	645	179	736	857	322	0	320	0	402	443	406		
C04	Try 1	546	0	702	224	280	0	279	0	567	0	1462		
	Try 2	717	0	793	0	238	0	326	0	372	0	331		
	Try 3	716	0	876	0	242	0	290	0	492	0	586		
C05	Try 1	390	0	723	0	211	0	220	0	798	0	404	0	613
	Try 2	423	0	822	0	214	0	246	0	759	0	487	0	720
	Try 3	433	0	804	0	230	0	249	0	667	157	416	0	448
C06	Try 1	391	292	199	1163	277	0	308	0	704				
	Try 2	464	195	487	880	262	0	287	0	1134				
	Try 3	477	213	606	742	275	0	336	0	937				
C07	Try 1	550	346	187	0	468	0	729	157	1038				
	Try 2	576	263	335	0	268	0	818	229	1229				
	Try 3	617	227	265	0	264	0	610	121	1156				
C08	Try 1	364	682	732	418	330	0	1238	0	308				
	Try 2	424	436	127	731	342	0	1355	0	479				
	Try 3	492	387	830	0	807	0	602	661	373				

Table A.6: Ukulele rhythm data of Group *Aud* (Audio Signals only) in milliseconds.

All further data and programs can be found under:
https://github.com/Selktro/Teaching-Rhythm-Via-Passive-Haptic-Learning

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