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Impact of Passive Haptic Training on Finger Dexterity

Bachelor's Thesis

by

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Erklärung

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Karlsruhe, den 19.11.2020

Abstract

Piano playing is enjoyable and advanced playing is impressive. However, practising is time-consuming, especially doing daily exercises to improve one's piano technique.

Kevin Huang et al. presented in their study 'Mobile Music Touch: Mobile Tactile Stimulation For Passive Learning' a prototype for learning piano songs trough tactile stimulation of the fingers while doing other unrelated tasks. Studies proofed that this prototype is effective in learning piano songs passively [5, 6]. However, these piano songs are on a beginner level of difficulty. Advanced pianists could play them on the spot without practice. Inspired by MMT, this thesis investigates the impact and the limitations of passive haptic training of finger dexterity[1]. Finger dexterity is an essential part of piano technique, and it is necessary for playing all kinds of scales rapidly.

A prototype for a haptic glove that trains finger dexterity trough vibrotactile stimulation is presented. The haptic glove consists of 5 vibration motors, one microcontroller and one Bluetooth module. The motors are placed on knuckles of the fingers—one motor for each finger. A vibrating motor simulates the corresponding finger stroking a piano key. During the passive haptic training, the duration of motor vibration is continuously and gradually shortend to simulate an increase of tempo.

An experiment evaluated the prototype. A total of 20 subjects with no experience in piano playing were tested. The subjects were randomly divided into two groups; an active and a passive group. First, they learned to play and repeat three technical exercises improving finger dexterity. For each participant, two exercises were selected randomly. Then, they practised these two exercises for 25 min each, either by using the haptic glove or actively, depending on their group assignment. The remaining exercise was not trained at all. After the training, they performed all three exercises again. Differences between their initial and their final performance were analyzed.

The analysis of the experimental results showed that subjects of the passive group, as well as subjects of the active group, could play trained exercises more fluently and with less hesitation. Consequently, they played them at a higher tempo. However, no significant improvements could be observed regarding the accuracy or the evenness of performances after training. The active group improved slightly more than the passive group. It was concluded that passive haptic training does not increase finger dexterity because accuracy and evenness did not improve significantly. Furthermore, active training was considered more effective but also more exhausting. Finally, it was concluded that active and passive training do not improve general finger dexterity in the short term.

[1]This thesis always refers to finger dexterity in the context of piano playing.

Kurzfassung

Fortgeschrittenes Klavierspiel macht Spaß und ist beeindruckend. Die meisten Menschen haben zu wenig Zeit zum Üben und machen deshalb keine Fortschritte. Kevin Huang et al. präsentierten in ihrer Studie „Mobile Music Touch: Mobile Tactile Stimulation For Passive Learning" (MMT) einen Prototypen, um Klavierstücke passiv haptisch zu lernen[6].

Die Stücke, die man mit MMT lernen kann, sind auf leichtem Anfängerlevel. MMT hilft dem Übenden nicht weiter, um fortgeschritten Klavier zu spielen. Auch wird Klaviertechnik nicht durch dieses Training verbessert. Klaviertechnik ist aber entscheidend, um ein fortgeschrittenes Niveau zu erreichen.

Diese Arbeit stellt einen von MMT inspirierten Prototypen vor, um passiv haptisch die Fingergeläufigkeit, die ein wichtiger Teil der Klaviertechnik ist, zu trainieren. Außerdem wird untersucht, ob der Prototyp tatsächlich einen positiven Einfluss auf die Fingergeläufigkeit hat. Unter Fingergeläufigkeit versteht man das kontrollierte Zusammenwirken von sauberem Tastenanschlag, sowie gleichmäßigem und schnellem Spiel.

Ein drahtloser Handschuh, ausgestattet mit fünf Vibrationsmotoren, einem Microcontroller und einem Bluetoothmodul soll die Fingergeläufigkeit durch vibrotaktile Stimulation trainieren. Die Vibrationsmotoren sind auf den Rücken der Finger platziert. Vibriert ein Motor induziert das, dass der entsprechende Finger eine Taste auf dem Klavier spielt. Das Vibrationstempo erhöht sich kontinuierlich und stufenweise, um eine Temposteigerung des Spiels zu simulieren.

20 Probanden wurden in einem Experiment untersucht. Sie wurden nach dem Zufallsprinzip in zwei Gruppen eingeteilt. Anschließend lernten beide Gruppen drei technische Übungen zur Steigerung der Fingergeläufigkeit. Jeder Proband der ersten Gruppe trainierte zwei zufällig ausgewählten Übungen mit dem Prototyp passiv; die andere Gruppe trainierte ebenfalls zwei zufällig ausgewählte Übungen, aber aktiv. Anschließend spielten die Probanden wieder alle drei Übungen. Die nicht geübte Übung diente einerseits dazu, die Wirkung von passivem haptischem Training auf die allgemeine Fingergeläufigkeit, welche unabhängig von dem zugrundeliegenden Stück ist, und andererseits, um die Effektivität des Trainings zu untersuchen.

Das Experiment zeigte, dass die Zeit, die gebraucht wurde, um eine technische Übung durchzuspielen, sich signifikant reduzierte, unabhängig davon ob sie aktiv oder passiv trainiert wurde. Jedoch wurden die Stücke nicht gleichmäßiger oder akkurater gespielt, nachdem sie passiv haptisch trainiert wurden. Es stellte sich außerdem heraus, dass aktives Training ein wenig effektiver ist als passives Training. Eine Wirkung auf die allgemeine Fingergeläufigkeit konnte weder für aktives

noch für passives Training nachgewiesen werden. Die Schlussfolgerung ist, dass haptisches passives Training dabei hilft, eine Sequenz von Noten flüssiger und mit weniger Zögern zu spielen. Eine Verbesserung der Fingergeläufigkeit konnte aber nicht nachgewiesen werden.

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1. Introduction

1.1 Motivation

Piano playing is enjoyable and advanced playing is impressive. Many people want to learn to play the piano, and many amateur pianists would love to spend more time playing. Having too little time or making slow progress are often-cited reasons why one does not start learning an instrument, or stops playing. To play the piano at a high level and to spend less time learning new pieces, a well-developed piano technique and regular practice are required. Developing a solid technique is time-consuming and takes years of practice.

Most non-professional pianists, especially working adults, do not have the time to practice regularly – and especially not for additional technical exercises. In comparison to regular pieces, specific technical exercises and etudes provide a more effective and quicker way to improve one's technique. However, these exercises usually lack any musical purpose and are not meant to be performed publicly. Hence, most amateur pianists pay little attention to them, which results in stagnation in their progress. Furthermore, technical exercises are exhausting for the wrist and the fingers. Doing exercises requiring the repetition of scales, 'octaves, and large chords often create tension, reducing blood flow', which can lead to injuries such as wrist tendonitis[1].

Previous studies have shown that passive haptic learning can be an effective way to improve motor skills. Huang et al. stated that subjects with no history in piano playing were able to perform simple piano pieces after 30 min of tactile stimulation[6]. These previous studies inspired this thesis. The success in learning easy piano songs trough vibrotactile stimulation brought the idea to train piano technique similarly.

The current paper examines passive haptic training of finger dexterity. Finger dexterity is an essential part of piano technique and it is necessary for playing all kinds of scales rapidly. Improving finger dexterity through passive tactile stimulation could help amateur pianists to make progress without spending more time practising. Additionally, tactile stimulation does not exhaust the hands, which reduces the risk of injuries. Success in passive haptic training of finger dexterity could lead to passive training of other piano techniques, and amateur pianists could become better at piano playing without investing substantial time.

A haptic glove was developed and evaluated by an experiment to investigate the impact of passive haptic training on finger dexterity. The findings were compared to data from subjects who had performed the same experiment, but were trained actively, to examine the effectiveness of passive haptic training. After reviewing previous research, I hypothesised that:

1. Passive haptic training affects finger dexterity on trained pieces positively
2. Passive haptic training does not affect the general finger dexterity[1]
3. Active training of finger dexterity is more effective than passive haptic training

1.2 Scope and Delimitation

This thesis discusses passive learning, especially the passive learning of piano pieces, as well as haptic learning and piano technique. The focus of the study is the impact of passive haptic training on finger dexterity. I examined whether the finger dexterity of subjects with no experience in piano playing could be improved through tactile stimulation. At the same time, the probands performed other unrelated tasks.

The thesis presents a prototype and an algorithm for passive haptic training, and evaluates them experimentally. A group of passive haptic trained testees were asked to perform technical piano exercises. A second group of testees performed the same experiment but they were trained actively. The results before and after the training were compared, as were the differences between the groups. The analysis examined the impact on finger dexterity and the effectiveness of passive training.

The study included only inexperienced testees; it did not include pianists and subjects who had more than one year of experience in piano playing in the last five years. Twenty testees of different ages and genders were tested. The experiment was limited to 30 min of passive or active training for each technical exercise. Passive training for more extended periods and its impact on finger dexterity was not examined.

1.3 Contributions

A previous study examined the effectiveness and limitation of passive haptic learning of piano songs. The muscle memory of the fingers was reinforced through tactile stimulation, which made it easier to remember the correct piano keys. As a consequence, the pianist made fewer mistakes. The research showed that this approach is an effective way to learn new pieces, especially for pianists with limited or no experience.

The contribution of this thesis is twofold. First, it examines whether passive haptic training affects finger dexterity; an approach to passive training of finger dexterity is presented and evaluated. Second, it investigates whether passive haptic training of finger dexterity is effective by comparing the results of active and passive training. Thus, this thesis examines whether passive haptic training of piano technique, as finger dexterity is s an essential part of piano technique, is thinkable.

[1]See section 2.4.2

1.4 Thesis Outline

The remainder of this thesis is organised as follows:

- Chapter 2 'Background and Related Work' provides the theoretical basis for this research. A brief introduction to passive learning, haptic interfaces and piano technique is given. Previous related research is reviewed.
- Chapter 3 'Passive Haptic Training System- Design' describes the implementation of the haptic glove and the corresponding computer software. The basic idea behind the passive training software is explained, and the concept of stepwise increasing tempo behind the algorithm is presented.
- Chapter 4 'Methodology' presents the experimental setup. Furthermore, it is explained how the data was gathered and analyzed.
- Chapter 5 'Experimental Results' presents an detailed description of the experimental results.
- Chapter 6 'Discussion' discusses the results and an evaluation of the hypothesis. Furthermore, questions that still require answers are discussed, and possible future studies are proposed.
- Finally, Chapter 7 'Conclusion' completes this work by summarising the main findings.

2. Background and Related Work

2.1 Passive and Active Learning

Learning is a process of gaining knowledge or skills or of changing behaviour. Learning occurs through studying or experience or by being taught. Usually learning is seen as an active process. Active learning 'holds learners responsible for their own learning' [13]. This approach is also described as 'A process in which students engage in "doing things and thinking about what they are doing" (Bonwell & Eison, 1991, p. 2)' [13]. Typical examples related to school are homework and group discussions. Regarding the topic of this thesis, developing finger dexterity through daily piano exercises – such as playing scales – can be considered as active learning.

Skill and knowledge that is 'caught, rather than taught' can be seen as passive learning [8]. The learner does not need to participate or do anything actively. They only need to be exposed to a source of information or stimuli, such as a teacher or media like radio and television. Researchers have observed passive learning in media-rich environments. In their article 'Passive Learning: When the Media Environment Is the Message', Cliff Zukin and Robin Snyder described differences between politically uninterested subjects in media-rich and media-poor environments. They reported that subjects living in media-rich environments were 40% more likely to acquire information than were subjects living in media-poor environments, when both groups were passively exposed to political information.

Passive learning can be characterised as 'effortless' and with an 'absence of resistance to what is learned' [10]. Passive learning is often considered less effective than active learning. Especially in class-specific materials, active learning leads to improved cognitive outcomes compared to passive learning. However, that is not always the case. In their study 'Mobile Music Touch: Mobile Tactile Stimulation For Passive Learning', Huang et al. found that unskilled subjects required fewer attempts to repeat a note sequence accurately when they learned them passively compared to learning them actively [6].

2.2 Haptic Wearable Interfaces

Humans acquire information through their visual, auditory and tactual senses. The tactual sense is made up of the tactile sense and the kinesthetic sense [18]. The difference is not discussed further in the following.

The 'tactile (or cutaneous) sense refers to the awareness of stimulation to the body surfaces [18].' The word 'haptics' is of Greek origin. It is derived from the verb 'haptesthai', meaning 'of or relating to the sense of touch' [17]. Manipulation of the tactual sense or perception through the tactual sense, or both, are generally termed 'haptics'.

In the past, the tactual sense was underutilised compared with vision and audition in the field of human–computer interfaces. Currently, research in haptics is broad and rich with opportunities [4, 18]. Every year, many papers and studies about haptics-related topics are published.

Wearable haptic interfaces or devices are essentially small robots that are worn. They take advantage of mechanical signals to provide communication between people and machines [4, 17]. Forms of this applied 'mechanical energy' for communication can be vibrations and force feedback, such as ultrasound or 'air vortex rings' or motion.

Haptics has developed a wide area of application and forms part of many topics in science and commerce, such as computer science, multimedia technology, medicine and mechanics. Haptic wearable devices are used for rehabilitation in medicine and as haptic feedback in video games, and for haptic learning. There are also many other applications.

2.3 Haptics and Learning

As mentioned above, learning is a process of gaining knowledge or skill. The learning process starts with sensory perception. Usually, regarding human information acquisition, the visual and auditory senses dominate. However, humans learn with all their senses [11], and the senses of taste and smell as well as the tactual sense are also employed.

Haptics can be a useful medium for training skills. Sensory perception is not sufficient for learning, because the sensory memory stores information only for several milliseconds or a few seconds. The stimuli must additionally be processed and stored in the long-term memory. One of the critical factors in establishing long-lasting memory is repetition. However, the focus on sensory perception is crucial. Distractions lead to a longer process of learning or incomplete storage of information in memory. A common distraction entails receiving multiple stimuli through the same sensory channel. Humans who experience this will prioritise one stimulus over the other [16]. For instance, listening to the radio while conversing with somebody makes it nearly impossible to listen to both equally attentively.

Up to now, passive haptic learning has been spoken of predominantly. However, Haptics is also used for active learning. A popular active haptic leaning methods is 'active haptic guidance' [7].

In his study 'The Impact of Haptic Guidance on Musical Motor Learning' Graham Grindlay proposed two active haptic guidance systems that provide a 'learning-by-feel' approach to percussion instruction [3].

The first system, Grindlay introduced, was the FielDrum. By using a combination of permanent magnets and electromagnets, FielDrum guides the drumstick top through the movements, that are required to perform rhythms. The Haptic Guidance System, the second system that was introduced, 'uses a servo motor and optical encoder pairing to provide precise measurement and playback of motion' [7]. The study showed that active haptic guidance could reduce note velocity errors and timing errors significantly.

2.4 Piano Technique and Finger Dexterity

2.4.1 Piano Technique

There is no wide consensus regarding a general definition of piano technique. Like every term that is not precisely definable, each expert has a different understanding of piano technique. In this section, several definitions are mentioned that describe my understanding of piano technique.

The piano pedagogue R. Kratzert defined piano technique as the pianist's availability of necessary capabilities for the tonal realisation of musical intentions [9, p. 13].

A simple and understandable explanation of piano technique can be found on the blog of the concert pianist Albert Franz:

> Piano technique is the ability to get the right sound at the right time out of the piano. [...] Piano technique could be thought of as the 'interface' between a musical idea and the music that comes out of the piano: Piano technique is our control over our instrument [8].

Well-developed piano technique allows the pianist to play what they want to play and how they want to play it. It is an important measure to distinguish accomplished and poor players. Piano technique is the most important tool to meet high musical expectations [9, p. 13]. Moreover, pieces at a certain level of difficulty, such as Liszt's Transcendental Etudes, cannot be played without a well-developed technique. Often-cited elements of piano technique are the playing of single notes; the playing of double notes, such as octaves and piano runs; and how to sit correctly at the piano. Finger dexterity is an essential element of piano technique, if not the most important element. Czerny wrote that 'Among the necessary qualities a performer upon the piano must possess, if not inclined to mediocrity, the regular dexterity of his fingers is the most important and ought to be applied to, the earliest possible' [2].

2.4.2 Finger dexterity

Finger dexterity in the context of piano playing can be defined as the ability to evenly and accurately touch the keys while playing at a fast pace[15].

A well-developed dexterity of the fingers is required to play almost all pieces containing runs without difficulty.

Several factors mainly influence finger dexterity:

First of all, the general motoric abilities of the pianist [9, p. 106]. Muscle strength and mobility of the fingers form the upper limits for how fast and cleanly a passage can be played.

Second, the Mental capacities of the pianist. The mental capacities include trivial elements like self-confidence. Some pianists do not have the courage to play fast because they are afraid to make too many mistakes. Mental capacities also include having full control over the fingers while playing a passage rapidly. After a little practice, it is not very difficult to 'tinkle' scales quickly on the piano. The biggest challenge is not the tempo; it is having control over the fingers at high pace [9, p. 107]. The pianist must be able to strike the keys precisely. He must be capable of exerting exactly as much pressure on a key as is appropriate to his musical intention.

Third, the specific pianistic factor, which includes the ability to memorize a specific piece or sight-reading, and much more besides, which is not discussed further.

The term general finger dexterity is regularly used in this work. In the following, when talking of finger dexterity, this means being able to play an already learned passage quickly and precisely. General finger dexterity means being able to play a passage quickly and precisely on the spot without having to practice it for a long time. While a critical factor in finger dexterity is how well a pianist memorises a passage, the coordination between mind and fingers is especially crucial in general finger dexterity.

While a person practises the piano, they develop the muscles and flexibility of their fingers. Furthermore, mind-to-finger coordination improves. Passive training through vibrotactile stimulation cannot improve muscle strength or flexibility of the fingers. However, it is assumed to improve elements of mental capacity and memorisation of the piece.

Consequently, active practising improves general finger dexterity, whereas tactile stimulation does not affect the development of mind-to-finger coordination. However, previous studies have noted that subjects played songs more smoothly and with less hesitation if they were trained with tactile stimulation [5, 6]. They could recall the right notes with less confusion and delay, indicating that tactile stimulation is a useful medium for storing piano songs in memory.

Hence, it was hypothesised that passive haptic training should improve finger dexterity when playing trained songs, whereas general finger dexterity should not be affected by passive haptic training.

2.4.3 Improving Piano Technique

From the beginning of piano teaching until today, some scholars have proposed that piano technique is mainly an inherited talent and can only be improved through practice [9, p. 13]. However, many experts hold different views.

There are two ways to improve one's piano technique. The first is through regular practice. For example, the muscles and flexibility of the fingers are enhanced by regular playing. Additionally, the player can gain a better feel for the piano keys and a more accurate musical ear. However, it can also impair the technique. Beginner pianists without supervision from a teacher to correct mistakes at an early stage often develop poor technique. Second, technical exercises and playing etudes can improve the player's technique.

Etude is a word of French origin (étude) and means study. The New Harvard Dictionary of Music defines etude as 'A composition designed to improve the technique of an instrumental performer by isolating specific difficulties' [14, p. 301]. An etude focusses on a technical problem in a specific area of technique, e.g. the independence of the fingers or finger dexterity. Through repetition of passages, that are challenging in this specific area, the technical problem will be mastered, and the technique improved. One of the most famous etudes-book for improving finger dexterity is Carl Czerny's 'The Art of Finger Dexterity' [2].

Technical exercises can not stand alone as a composition. They are short sections that focus on one technical problem and do not have any musical purpose. Typical examples of technical exercises are playing scales of single notes, accords or arpeggios. Technical exercises are a simple way to train the technique even for beginners because usually, one does not have to learn a new piece to practise a technical problem. However, some technical exercises are controversial, Hanon's 'The Virtuoso Pianist' [19] in particular. Critics disapprove the lack of musicality and variation, saying it leads to a mechanical way of piano playing.

2.5 Piano Touch and Mobile Music Touch

The paper: 'Mobile Music Touch: Mobile Tactile Stimulation For Passive Learning', published by Kevin Huang et al., was the inspiration for this thesis. Mobile Music Touch (MMT) is a wearable piano instruction system, that 'helps teach users to play piano melodies while they perform other tasks' [6], by using vibrotactile stimulation. MMT evolved from 'PianoTouch: A wearable haptic piano instruction system for passive learning of piano skills' (PT), which was presented by Kevin Huang, Ellen Yi-Luen Do and Thad Starner in 2008. PT 'is a wearable, wireless haptic piano instruction system, composed of: Five small vibration motors, one for each finger, fitted inside a glove. Bluetooth module mounted on the glove. Piano music output from a laptop' [5].

The study investigated the potential of the system of passive learning of piano pieces [5]. Four subjects were tested to investigate the differences between learning piano songs with and without tactile stimulation. The subjects active learned two songs initially with 'tactile sensations for both songs, watched a virtual piano on the laptop playing the songs, and practiced until they could play both songs without mistakes' [5]. Afterwards, they performed other, unrelated tasks for 30 minutes. During this time, two of them received tactile stimulation for one song and for the other, they did not. The remaining two subjects received tactile stimulation for the other song. 'The study found that after 30 minutes, the Piano Touch subjects were able to play the song accompanied by tactile sensations better than the non- tactile song' [5].

As mentioned, MMT evolved from PT. In their publication, Kevin Huang et al. presented two studies on the efficacy of MMT. The first study measured '16 subjects' ability to play a passage after using MMT for 30 minutes while performing a reading comprehension test' [6]. The second study compared 'the amount of time required for 10 subjects to replay short, randomly generated passages using passive training versus active training' [6]. In the first study, subjects learned to play melodies on the piano by receiving tactile stimulation and audio or just audio. The audio 'playback occurred with both phrases, but only one phrase had tactile stimulation' [6]. In the meantime, the subjects performed a reading comprehension test. The results showed that the MMT system was significantly more effective than the passage, where the subjects received repeatedly audio playback, but their fingers were not vibrated [6]. Moreover, it was also found that the subjects performed poor on rhythm in pieces they learned with MMT. The second study compared the attempts required between subjects with piano experience and unexperienced subjects to repeat a note sequence. Subjects with piano experience needed fewer attempts than inexperienced subjects when learning actively. However, participants 'with no piano experience could repeat the passages after passive training while subjects with piano experience often could not' [6].

MMT has recently been widely researched not only for learning piano pieces. Tanya Markow examined in her thesis the potential of MMT in rehabilitation [12].

The piano songs learned by MMT and PT were songs on a beginner level of difficulty. Advanced pianists could repeat these songs on the spot without practising; that is why MMT is of little use when playing the piano at an advanced level. When wanting to play famous classical compositions, hours of practice are required and additionally well-developed technique. This work aims to lay the foundation for investigating whether piano technique can be improved through passive haptic training by examining the influence of passive haptic training on finger dexterity.

3. Passive Haptic Training System - Design

This chapter describes the functionality and design of the passive haptic training system. In the rest of this thesis, the passive haptic training system is abbreviated to HATS, for '**HA**ptic **T**raining **S**ystem'. HATS consists of two main components, namely computer software running on a device such as a laptop, which communicates with and controls the second component, a haptic glove. The system was designed for use in an experimental environment. It was designed to satisfy all experimental requirements with the least effort and therefore had limited functionality.

3.1 Basic Functionality of HATS

The HATS trains finger dexterity passively, through vibrotactile stimulation of the fingers. A computing device and the haptic glove together form the HATS. A vibration motor is placed on each finger of the haptic glove. When a motor vibrates, this indicates that the corresponding finger should press a key on the piano. In this way, playing the piano is trained passively. The software on the computing device communicates to the haptic glove which motor should vibrate and for how long.

The procedure of the training is illustrated in Fig. 3.1. First, the software reads the piece or exercise to be trained. Then it communicates to the haptic glove how the motors should vibrate according to the piece. The glove merely executes the software instructions.

In piano practice, a popular method to master a difficult section of a piece and to train finger dexterity is through stepwise increases of the tempo. It is a relatively simple approach. The pianist starts at a slow tempo – so slow that the player is in full control of the section. They practice it for long enough to become able to play the section without errors. Each note and rest must be played accurately and according to their values. The pianist must be able to play the section precisely, as it is written in the score, with near mechanical perfection. Once the player can do so, the tempo of the playing is increased a little and they start to practise the section

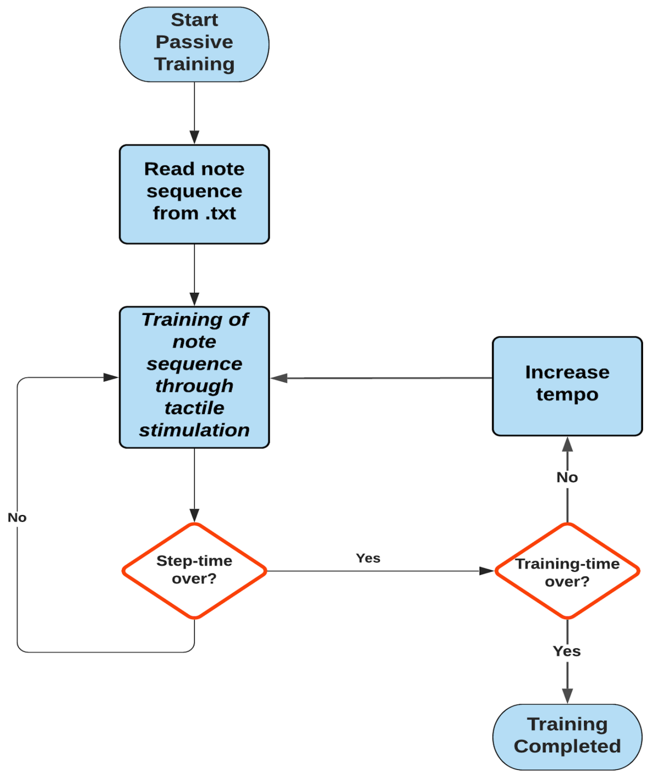


Figure 3.1: Flowchart of the training process

slightly more rapidly, until perfection is reached again. The procedure is repeated until the pianist can play the section neatly at the desired final tempo.

The HATS realises this approach. The software implements a stepwise increased-tempo algorithm 3.7 that was developed for this experiment. The computing device increases the tempo of the piece being passively trained repeatedly after a specific period, known as the step interval. It does so by communicating to the haptic glove to reduce the duration of a motor's vibration.

The training is executed for a specific period. During this interval, the vibration pattern of the piece is constantly repeated, and the tempo is increased continuously and incrementally.

3.2 Haptic Glove

The MMT Glove inspired the haptic glove. The MMT Glove received mixed reviews from participants regarding its comfort. Some participants said the material had to be changed if the glove was to be worn for a more extended time [6]. This feedback was taken into account during the requirements analysis. The main requirements for the glove were that the vibrating motors could be felt and that the glove was comfortable and not restrictive. Furthermore, it was essential for the motors to function precisely, even if the period of oscillation was only a fraction of a second. The periods of motor vibration is constantly reduced during operation. It must not happen that two motors vibrate at the same time due to a delay in the component turning on; similarly, it cannot happen that one motor does not start vibrating at all.

Requirements for this study

- The glove should be comfortable to wear
- The glove should be light and barely noticeable
- The connection with the computing device should be stable
- It should be possible to control the vibration motors precisely, even when vibration duration is minimal

Components of the glove

The haptic glove consists of similar components as the MMT :

- Five vibration motors
- Bluetooth-module and microcontroller
- Three PWM driver chips
- One battery
- One glove

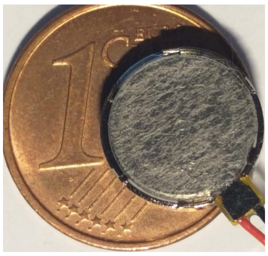


Figure 3.2: Image of a vibration motor

An arthritis compression glove was used as the basic glove. A symptom of arthritis is temporarily swollen fingers; hence, gloves for treatment must be tight and hard-wearing while also being highly flexible. They should fit even if the fingers are swollen. This makes the glove ideal as a base, as it fits almost all subjects, who have fingers of different thickness and size. It still fits tightly enough for the motors to be sensed.

The glove fingers were cut off so that the glove would be less of a hindrance in everyday tasks. Precision Mi- The fingertips of the were cut off so that the glove would be less of a hindrance in everyday tasks. Precision Microdrives model # 310 -101 were used as vibration motors for the haptic glove (**??**). The motors were glued on the back of the fingers, one on each finger, just below the knuckle. The motors were soldered to the three PWM driver chips. Two motors for the fingers were connected to a PWM driver chip. The thumb motor was connected to one chip on its own. The driver chips were chained. Thus, they enabled precise control of the motors while making it possible to use microcontrollers with few Input/Output Pins.

The BLE Nano 2 from RedBear was used as a microcontroller and Bluetooth module (see Fig 3.3). The BLE Nano 2 communicated with the computing device via Bluetooth and controls the vibration motors according to the computing device's instructions. The microcontroller was powered by a 600-mAh battery with 3.7 V, which allowed the glove to be used wirelessly.

Limitations in glove design

- Placement of vibration motors is not adjustable
- Short battery lifetime
- Only one-way bluetooth communication is supported

During the experiment, the motors were noted to be placed far forward on the fingers of people with small hands. In future research, it would be useful to adapt the placement of motors to the hand of the wearer. It was also found that the batteries needed to be changed after only about five hours of operation. Finally, the wearable device merely executes the instructions it receives from the computing device, and no confirmation or error messages are sent to the software.

Subjects found wearing the glove comfortable and minimally disturbing. See 5.4. However, it was particularly difficult to take the glove off, because the material is very flexible and there was a risk that if one pulled too hard, the wires would tear. Components were either sewn on, glued or attached with Velcro fasteners. They were not placed on the back of the hand in a box as with MMT. Some subjects thus felt restricted because they were afraid of damaging the glove through incorrect movements.

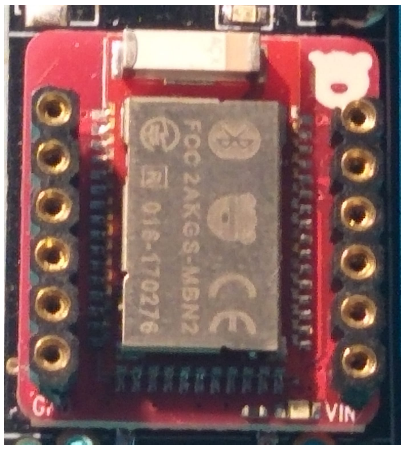


Figure 3.3: Image of the Redbear BLE Nano 2

Final Product

The Finale product could meet almost all requirements. The subjects found the wearing of the glove little disturbing and comfortable (5.4). However, it was particularly difficult to take the glove off, because the material is very flexible and there was a risk that if one pulled too hard, the wires would tear. Components were sewn on, glued or attached with velcro fasteners, and not placed to the back of the hand in a box. Consequently, some subjects felt restricted because they were afraid of damaging the glove through wrong movements.

The microcontroller could establish a stable Bluetooth connection with the software.

The vibration motors switched precisely at a vibration period of 125 ms (= note value 1/ 16 at 120 Bpm) and thus also fulfilled the requirements.

The final result of the haptic glove is displayed in Fig 3.4.

Figure 3.4: Image of the haptic glove.

3.3 Software

The main tasks of the software were to read the musical piece to be trained and to execute passive training while communicating and controlling the haptic glove. The software was programmed in Python 3.8.5. Python was chosen mainly because extensive packages and libraries for Bluetooth Low Energy are provided for Python. Furthermore, Python is platform-independent, and it is a productive language.

Requirements

- stable, error resistant bluetooth communication
- uncomplicated and quickly developable
- modifiable and extendable

The requirements for the software were on the on hand that the software fulfils all essential functions necessary to control the glove, e.g. Bluetooth communications. On the other hand, it should be easily expandable. The software should be more comfortable to use and training possibilities, e.g. training modes so that it can be used for further research in the future. For the sake of completeness, the planned extensions are described under Limitations in this subsection.

Particularly important was a reliable Bluetooth communication, so that transmission errors which could influence the experiment results do not occur. Furthermore, the development of the software needed to be minimally time-consuming so that more time could be spent on the experiment and evaluation.

The UML sequence diagram illustrates the interactions of the software components that realize the passive training on the software side. First, the piece that should be trained is read from a .txt - file and converted to a byte array. The software supports only .txt-files as input for note sequences. The .txt-file contains numbers in the range from 1 to 5, indicating the fingering required to play the piece, and therefore which motor should vibrate. The 1 corresponds to a motor placed on the thumb, the two to the index finger etc. A small section of example-file is shown in Fig. 3.5.

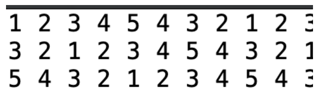


Figure 3.5: .txt-file to read ”vibration sequence” for exercise 01.

The file is converted into a byte array because byte arrays are particularly suitable for Bluetooth communication. Then, the training is executed. The training time and the starting tempo is configurable, for the experiment was set to 25 min and 60 bpm. The implementation of the Stepwise Increasing Tempo Algorithm in the Training class is what executes passive training. Its interactions are illustrated in the sequence diagram between the classes Training and BLE Manager, and the actor Wearable.

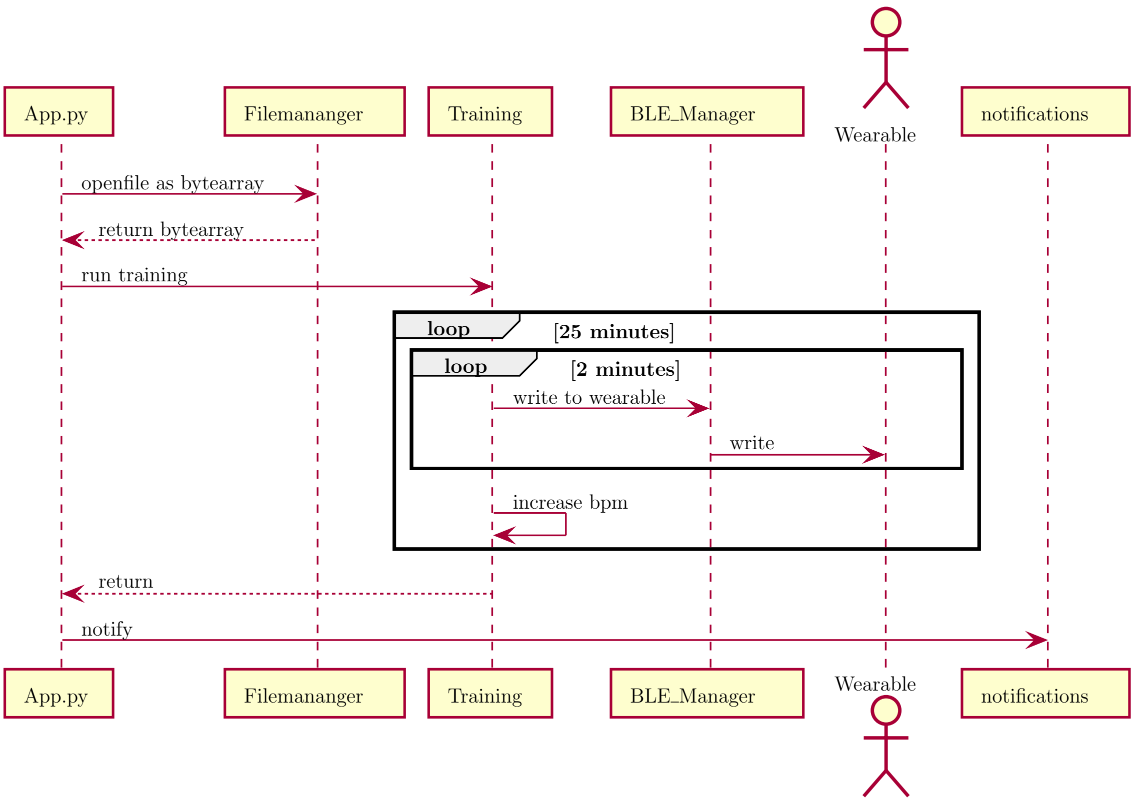


Figure 3.6: UML sequence diagram illustrates the interactions that realize the passive haptic training

The Bleak client software provides the necessary functions used by the BLE Manager to establish a Bluetooth connection and communicate via Bluetooth. The main reasons for choosing Bleak were that it comes with an MIT license and that the

Bluetooth functions are implemented on a high level, enabling easy and productive programming. Furthermore, Bleak is platform-independent. During each training step (See inner loop sequence diagram), the BLE Manager sends the instructions, how motors should vibrate to the wearable. Afterwards, the tempo, at which the motors should vibrate, is increased. Once the training time is up, a notification is sent to the notification centre of the computing device´s operating system, to signal the user that the training of the exercises is over.

3.3.1 Stepwise Increasing-Tempo Algorithm

The core of the software is an algorithm that executes passive training through stepwise increases in tempo. As long as the training time is not completed, the algorithm runs these steps. Each step lasted 2 min. A preliminary experiment with two subjects showed that the pace of playing technical exercises could be increased every 2 min. The participants were asked to play technical exercises similar to those that would be performed in the main experiment. The time they needed to learn to play the exercise correctly and evenly was measured. On average, they needed 1 min 48 s, which was rounded up to 2 min.

During each step, the algorithm calculates the duration for which a motor should vibrate. It then sends the number of the motor that should vibrate, and the duration, via Bluetooth to the glove. After 2 min the step is complete. If the training time is not complete, the pace increases and the next step starts. The next step repeats these actions with the new pace, again for two minutes.

Algorithm 1: Step-wise Increasing Tempo Algorithm

```
Function Run_passive_training(piece : list, timeout, bpm: int):
    step_timeout ← 2
    while time < timeout do
        delay_in_sec ← bpm_to_sec(bpm)
        while time < step_timeout do
            write_to_wearable(piece, delay_in_sec)
        bpm ← increase_bpm(bpm)
```

Figure 3.7: Step-wise Increasing Tempo Algorithm

The parameters of the algorithm were as follows:

- piece: the musical piece as a list of byte arrays
- timeout: the duration of the passive training in minutes as an integer value
- bpm: the start pace in beats per minute as an integer value

Each element of the byte-array list represents a note of the musical piece. In other words, a piece consisting of 25 notes would correspond to a list that contains 25 arrays, with each array storing the byte code that indicates which motor should vibrate to play the represented note.

The algorithm calls three procedures. The first is *bpm_to_sec(bpm)*, which takes the tempo (measured in beats per minute) and returns the duration each note should last in seconds, as a float value. Since all technical exercises in the experiment consisted solely of notes having the same note value, other cases were not considered.

The second procedure is *write_to_wearable(piece, delay_in_sec)*. This procedure sends, via Bluetooth, the list containing the sequence in which the motors should vibrate and the duration of each note to the haptic glove.

Third, *increase_bpm(bpm)*. This procedure checks whether the maximum pace has been reached. If not, the pace for the next step is increased by eight beats per minute.

The final Python implementation of the algorithm is shown in Figure 3.8, with minor changes for practical reasons. The algorithm is implemented asynchronously. The write-to-wearable procedure was provided by a ble client object, which provides functions to establish Bluetooth communication properly and to handle communication errors.

```python
async def run(self, piece_as_bytearray: bytearray, duration_min=30, start_bpm: int = 60):
    timeout = self.__get_timeout_fom_minutes(duration_min)
    bpm = start_bpm
    async with ble() as ble_client:
        while time.time() < timeout and self._running:
            step_timeout = self.__get_timeout_fom_minutes(2)
            delay_in_sec = self.__bpm_to_sec(bpm)
            while time.time() < step_timeout and self._running:
                await ble_client.write_to_wearable(piece_as_bytearray, delay_in_sec)

            bpm = self.__increase_bpm(bpm)
            await asyncio.sleep(3)
```

Figure 3.8: Python Code of the Stepwise Increasing Tempo Algorithm

Limitations of the software

- Only .txt-files can be processed; .midi -files are not supported
- Rhythm of pieces is disregarded
- Chords are not supported

The software only supports .txt as input format for music pieces due to the time limitation of this work. As a consequence, the software disregards note values and rests so that no rhythm can be trained.

It is planned to extend the software, that .midi-files are supported. An algorithm should be implemented, that automatically maps the ideal fingerings to notes in a midi file. Furthermore, the software should transmit pauses and note length to the haptic glove in addition to the numbers, which motor should vibrate. The haptic glove already supports, that multiple motors vibrate at once. It is planned to implement training of chords in the future, too.

4. Methodology

The haptic training system (HATS) was evaluated by an experiment with 20 subjects who had little or no experience in piano playing. Experienced or professional pianists, who have years of practice, would not make notable progress during the experiment, which would have led to unusable results.

The primary goal of the experiment was to examine whether finger dexterity could be improved through tactile stimulation of the fingers. A secondary focus was how effective the passive training of such finger dexterity might be. The test subjects played technical exercises and the initial performances were recorded; then they were trained in the exercises either passively, actively or not at all. Thereafter, they played the exercises again, and the differences compared with the original recordings were analysed.

All exercises were played on a Korg M50 keyboard. The keyboard was connected to a laptop. The performances were recorded on the laptop using Presonus Studio One 5. In the following, the first and final recordings are referred to as ‘first round’ and ‘second round’.

4.1 Experimental Structure

4.1.1 Participants

Twenty participants were tested to evaluate the HATS and to examine the effectiveness of the various training methods. They were divided randomly into two groups, with 10 participants each. The first group, the passive group, was trained passively in the exercises using the HATS. The second group, the active group, trained actively. Both groups learned the same three technical exercises.

It was desirable to enrol subjects who were as diverse as possible. The requirement for all subjects was that they should not have played the piano regularly in the last five years. Hence, all subjects were asked about themselves and their musical education before the experiment. The following questions were asked before subjects were randomly assigned to the groups:

Pre-experimental Questionaire

1. What is your age?
2. What is your gender?
3. Have you ever had piano lessons or learned to play the piano?
4. Have you played hardly any or no piano in the last five years?
5. Are you practising any other instrument regularly?

The initial data analysis showed that the average age in the passive group was 31.3 years, and in the active group it was 27.8 years. The youngest subject was 18 years old and the oldest was 70. Nine of the 20 subjects were female and 11 were male. The subjects had different musical backgrounds: 18 had never learned to play the piano and two had received lessons at a young age. Five subjects who lacked piano experience played another instrument and had some musical education; the other 13 subjects had never learned an instrument or had any musical education.

After the experiment, they were interviewed again. This time the questions differed according to which group the subject belonged to.

Post-experimental Questionaire, Passive Group

1. Did you notice the vibrations? Were they disturbing?
2. Was the glove comfortable or uncomfortable?
3. Do you have the impression that making the vibrations continuously faster helps to improve finger dexterity?
4. Does your hand feel exhausted?

Post-experimental Questionaire, Active Group

1. How exhausting was practising the exercises (1 - 10)?
2. What did you find particularly difficult about practising actively?
3. If you played the piano, would you do technical exercises?
4. Does your hand feel tired or numb?

The results for the post-experimental questionnaire are presented in section 5.4.

4.1.2 Technical Exercises

Charles-Louis Hanon's "The Virtuoso Pianist"[19] inspired the three technical exercises in this experiment. His technical exercises are easy to learn, similar to each other and do not require musical understanding. Hence, they fitted the purpose of this research and the exercises in the experiment. Three sections of his exercises were selected, shortened and simplified to be suitable for inexperienced subjects. Furthermore, they were transformed into exercises for the right hand only. See Fig. 4.1, Fig. 4.2 and Fig. 4.3.

Each exercise had a different focus and was of easy to medium difficulty for beginners; the first was the easiest and the second was the most difficult. Almost all subjects confirmed this trend and only two people felt that all pieces were equally challenging. The notes to be played were repeated according to a sequence, which made it easier to perform them correctly and without hesitation because less thought was required to determine which note was played next. It depends almost entirely on the dexterity of the fingers. The first piece was the easiest to play because the sequence of notes was straightforward, which allowed the player to concentrate mainly on speed during a performance.

Exercise 01

Figure 4.1: Piano score for Technical Exercise 01

The second exercise can be considered the most difficult of the three in terms of errors. The counterpart notes make this piece challenging, especially for fast performances.

Exercise 02

Figure 4.2: Piano score for Technical Exercise 02

The third and last exercise focuses on evenness. It requires self-control and finger control to play the middle part at the same tempo as the beginning fifth from the first to the second note of a sequence. Beginners tend to rush in the middle part.

4.1.3 Passive Group

The members of the passive group trained their finger dexterity using the HATS. After a brief instruction, they learned all three technical exercises, one after another. As soon as a subject was able to repeat a technical exercise at least moderately well, they were asked to perform the exercise entirely while it was recorded. The recording was stored as a Midi file.

The performances of all three exercises were recorded in the first round. Then, two exercises were selected randomly and were trained using the passive HATS. The

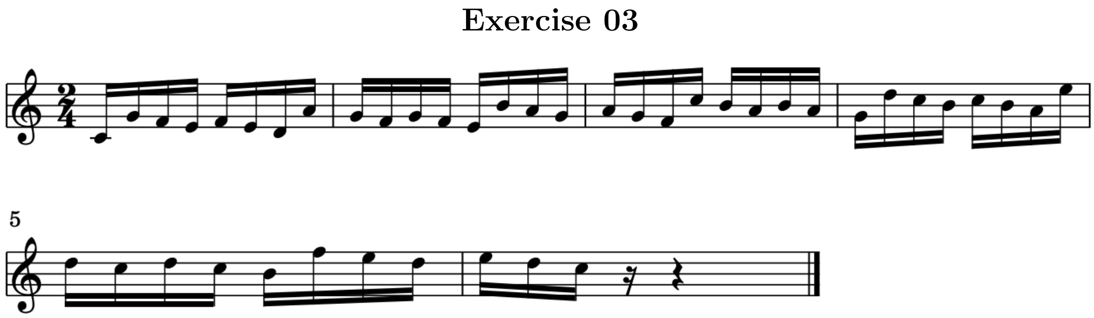


Figure 4.3: Piano score for Technical Exercise 03

remaining exercise was not trained. This approach was followed for two reasons. The first was the need to determine whether the passive training system influenced general finger dexterity (i.e. dexterity independently of the runs to be played), or only the finger dexterity of runs that were trained with HATS. The second reason was to substantiate the effectiveness of the HATS. Almost no subjects had ever played the piano. Any improvement in finger dexterity should not be incorrectly attributed to the system if the actual reason was that the subjects felt more familiar with piano playing during the second round. This could happen if they gained some confidence in their piano playing in the first round.

After recording all exercises in the first round and selecting two of them randomly, the researcher gave the participant the haptic glove. The first of the selected exercises was then trained passively for 25 min. While being passively trained, the participant completed an online IQ test. The result of the test was irrelevant for this experiment; the purpose was solely to distract the subject through a challenging task so that they would not focus their attention on the glove's vibrations.

Once the training was completed, the participant performed the exercise just trained while it was recorded. The participant was given two attempts and the best was selected. The same procedure was repeated for the second randomly selected exercise. Thereafter, the remaining exercise, which had not been trained, was recorded immediately. Lastly, the participants were asked questions about their impressions of the HATS.

4.1.4 Active Group

The experimental procedure for the active group was similar. This group consisted of 10 participants. As with the passive group, they were asked to learn and record all three exercises initially. Again, two exercises were randomly selected and then trained; however, this time the training was active. The third exercise was not trained.

Like the passive group, the participants of the active group trained for the exercises for 25 min. The active practice was inspired by the method of stepwise increasing tempo (see section 3.1). The tempo was set by a metronome. Each participant started with a tempo of 60 bpm, and each note corresponded to one beat. The participants repeated the technical exercise at the given tempo until they could play it flawlessly and without hesitation.

After playing the exercise three times neatly, the tempo was increased by 8 bpm. The participants were then asked to repeat the exercise until they could play it at the faster tempo. This procedure was repeated until the time was complete. The exercise was then recorded; the participant had two attempts, and the best try was selected. The second exercise was trained in the same way.

The metronome was used only during practice runs. While the final exercises were recorded, the active group played freely. Thereafter, the third (untrained) exercise was recorded. Finally, the participants were asked questions about whether their hand was exhausted and if the training had been strenuous.

4.2 Data Analysis

As mentioned earlier, finger dexterity 2.4.2 means the ability to play at a fast pace, while touching the keys accurately and evenly. Hence, mistakes, pace and the evenness of subjects' performances were measured, to evaluate finger dexterity according to this definition. These three aspects are discussed below.

1. The **tempo** (pace) of a participant's performance was determined by measuring the time needed to play the technical exercises from beginning to end. The tempo was not converted into beats per minute (bpm), since the time in seconds of a performance is a more understandable unit and easier to compare. The keystroke speed was not measured. It was assumed that a shorter time to complete an exercise would indicate higher performance speed.

2. **Accuracy** means that the right note is played cleanly. If a participant played a wrong note (i.e. a note other than the one written in the score), it was considered a mistake. If multiple keys were struck at once, this was regarded as 'unclean' and was considered a mistake. For each exercise, the number of mistakes was counted to measure the accuracy of the performance.

3. **Evenness** means that each note and each rest should last according to their standard length and the tempo. In a performance with ideal evenness, each crotchet (quarter note) lasts equally long, as does the crotchet rest; a quaver (eighth of a note) lasts half as long as a crotchet, and so forth. All three technical exercises consisted of notes having equal value or length. This approach allowed measuring the evenness by calculating the standard deviation of note length.

First, only the exact length of the played notes was analysed to calculate the standard deviation. However, this turned out to be a rather inaccurate approach. In all technical exercises, the notes are played one after the other, without rests. However, at some point during a performance, many participants had to search for the next note while playing the runs, which led to staccato notes with longer rests in between. Hence, a small variance of note length indicated an even performance. Conversely, performances were often highly uneven. To remedy this measurement error, the statistical standard deviation of note lengths (4.1) and rest lengths (4.2) was calculated and analysed.

$$s_{notes} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}$$

where

x_i = duration of note delay
n = number of notes
$\bar{x}$ = arithmetic average note delay
s_{notes} = standard deviation of notes

(4.1)

Because no pause should occur between the notes, 0 was determined as the nominal value. Zero was thus also the arithmetic mean to calculate the standard deviation of the rests.

$$s_{rests} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - 0)^2}{n}}$$

where

x_i = duration of rest delay
n = number of rests > 0s
s_{rests} = standard deviation of rests

(4.2)

A software was programmed, to analyze the recordings after the experiment. The software extracts the exact performance length of the .midi-file and calculates the standard deviation of note lengths and rest lengths. Furthermore, the software determines the number of mistakes in performance by calculating the Levenshtein distance between the nominal and the actual notes. If a participant aborted his performance and restarted, the .midi-files were analyzed manually. The same applied if he accidentally played a sequence of notes twice in an exercise because it resulted in too many unrepresentative errors.

The experimental results were analyzed using two-tailed pairwise t-tests. The t-tests compared the initial performances of a group to its final performances in terms of tempo, accuracy and evenness.

A positive influence on finger dexterity was assumed if significant differences were found in measurements of tempo, errors and evenness between the first and second rounds. This assumption applied to all exercises during the experiment and for all training groups. A training method was considered to be most effective if the differences between the two rounds are more significant than with the other training methods.

Summary of Experimental Procedure

1. Administration of pre-experimental questionnaire
2. Active learning of all three exercises
3. Initial recording of all three exercises
4. Random selection of two of the three exercises
5. Passive or active training of the first exercise for 25 min
6. Final recording of first trained exercise
7. Passive or active training of the second exercise for 25 min
8. Final recording of second trained exercise
9. Final recording of third (untrained) exercise
10. Post-experimental questionnaire

Figure 4.4: Summary of the experimental procedure.

5. Experimental Results

Differences in tempo, accuracy and evenness within one group, before and after training (whether active or passive), were the focus of statistical analysis. The results presented in three subsections, one for each feature being investigated. All data gathered in the experiment are listed in Appendix A. For each exercise, four scenarios were considered in evaluating the data. These cases were as follows:

1. Performance by subjects in the passive group
2. Performance by subjects in the active group
3. Performance by passive group subjects who were not trained on a specific exercise
4. Performance by active group subjects who were not trained on a specific exercise

The last two cases listed do not imply that the subjects have not trained at all. It just indicates that they have not trained a particular exercise, which was once the case for each subject for precisely one exercise. For example, a description of 'passive group, no training for exercise 1' refers to subjects who did not train in exercise 1 but did train in the other two exercises, passively. When speaking of exercises two, the same term refers to other subjects. The terms are equally used in the following subsections.

5.1 Tempo

Tempo is the pace at which a section of a musical piece is played; it is usually measured in beats per minute (bpm). For the experimental evaluation, tempo was measured as the time in seconds from the first note played until the end of the last note played in the performance. It was assumed that the shorter the time needed to complete an exercise, the faster the performance.

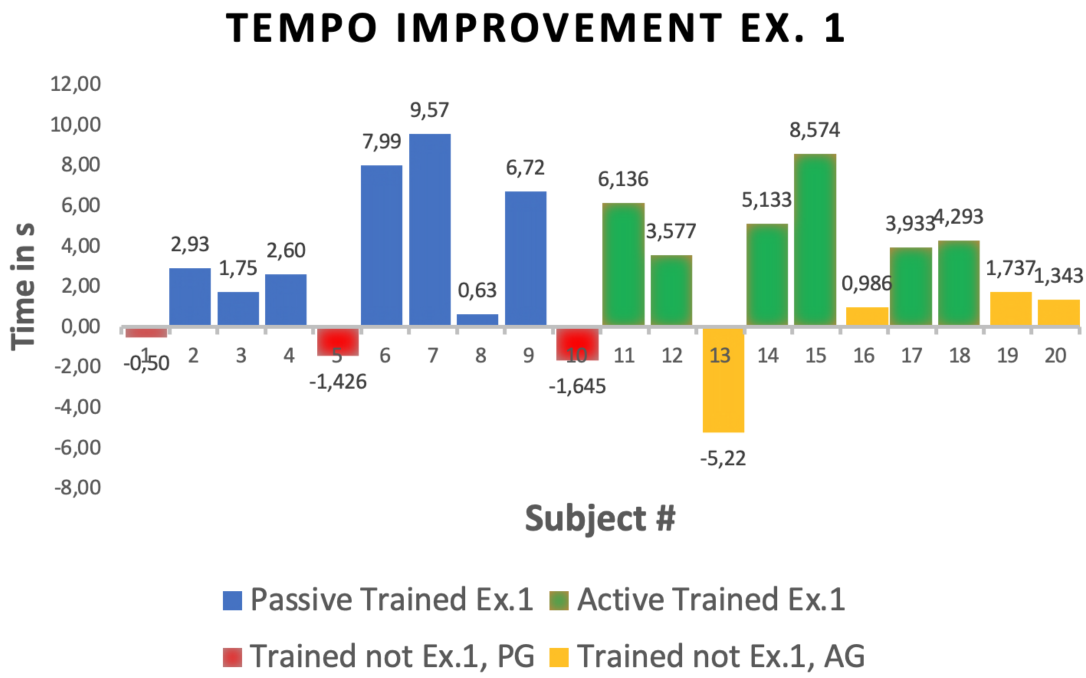


Figure 5.1: The bar chart illustrates the tempo improvements in seconds for Exercise 1 for each subject after the training

Figure 5.1 indicates that all subjects who were trained decreased their performance time noticeably. Their results are summarised next; the results for subjects who did not train are then presented.

The passive group needed on average 22,79 s to complete the first exercise. After using HATS for 25 min, the average time decreased by approximately 4,5 s to 18,20 s. This was an improvement of 20,14 %.

Subjects who had a worse starting value improved more than subjects who had a better initial value, with the difference being significant. The only exception was item 6, which needed fewer than 20 s at the beginning, which was above average; the result improved by 6 s to 11 s in the second run. The latter result is almost in the range of advanced pianists.

A paired t-test showed that the difference in the average duration before versus after the training was significant. The t-tests results (before vs. after training) are listed for all four cases (4.2) in Table 5.4.

The active group improved more than the passive group. Starting with a similar value of 23,14 s, they needed only 17,86 s after practice. This was a decrease of 22.82 %.

A highly similar trend was observed for exercise 02. Again, all subjects who trained improved their tempo noticeably, except subject 1. This subject needed approximately 0,3 s longer for the second exercise, possibly because his starting time was 10,53 s; this was unusually fast and was well above the group's average time.

The average performance time of the passive group before training was 22,95 s and for the active group it was 22,69 s. Both groups improved by about 20%, with

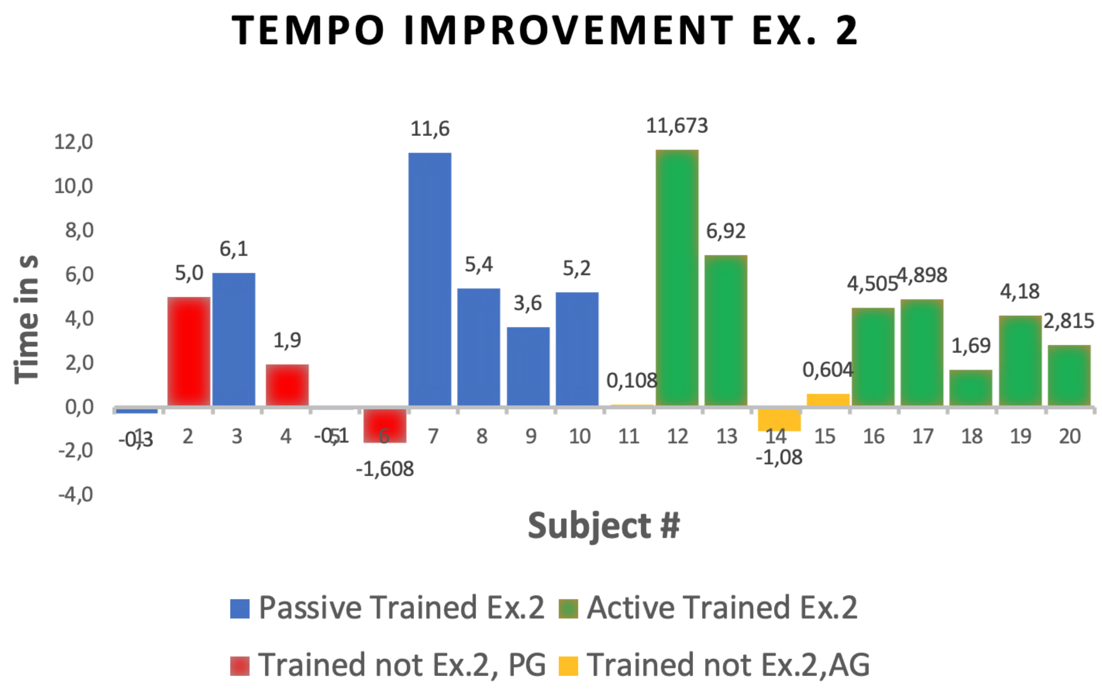


Figure 5.2: The bar chart illustrates the tempo improvements in seconds for Exercise 2 for each subject after the training

the active group again outperforming the passive group. The results of the third exercise followed the same trend. The passive group improved by 16,91% and the active group by 21,25%.

The passive group was expected to be outperformed by the active group. However, the passive group improved more than assumed. The t-tests confirmed that the post-exercise speed changes were significant for each trained exercise and for both groups.

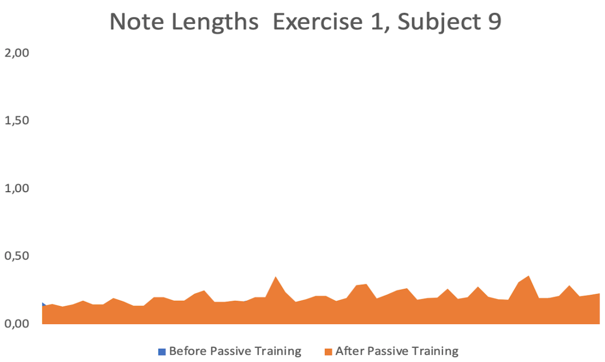
Regarding the subjects who did not train for specific exercises, there was no clear direction of development. In all three exercises, performance sometimes improved and sometimes worsened. Nonetheless, their improvements were significantly less than for the groups that had trained. However, subject 2 decreased the time needed by 5 s for exercise 2; this was surprising as exercise 2 was the most difficult of the three, and this with an average initial value.

Subjects of both groups worsened on average in playing the first exercise but improved slightly in exercises 2 and 3; this result was surprising since the first exercise was the easiest of all three. The initial performances were always recorded in ascending order. Hence, the general poor performance on the first exercise could be related to the fact that it was learned earliest. Therefore, more may have been forgotten by the end than with the other two. The t-tests results showed that improvements in untrained exercises were not significant See 5.4.

The tempo increase seemed to be mainly related to the fact that the subjects were more familiar with exercises after the training. It did not necessarily imply that they had developed better control and faster finger movements.

Tempo - t-Tests: Paired Two Sample for Means, P(T<=t) two-tail				
Ex. #	**Passive Group**	**Active Group**	**Passive Group w/o T**	**Active Group w/o T**
1	$p < 0,0124\,(S)$	$p < 0,0001\,(S)$	$p < 0,078\,(NS)$	$p < 0,88\,(NS)$
2	$p < 0,026\,(S)$	$p < 0,0055\,(S)$	$p < 0,45\,(MS)$	$p < 0,83\,(NS)$
3	$p < 0,01\,(S)$	$p < 0,001\,(S)$	$p < 0,89\,(NS)$	$p < 0,088\,(NS)$

Table 5.1: Pair-wise t-test results for comparisons of tempo improvements. P-values for each training and exercise are given. Significance is stated as significant (S), p < 0.05, marginally significant (MS) 0.05 < p < 0.075 and not significant (NS).



(a) Area chart illustrates length of each note in s of subject 9's initial and the final performance.

(b) Area chart illustrates length of each pause in s of subject 9's initial and the final performance.

Figure 5.3: Results of detailed analysis of subject 9's exercise 1 performances.

Every note length and every pause length in all performances was inspected, to verify the suspicion. An example of such confirmation can be seen in Fig. 5.3.

Subject 9 improved his tempo for exercise 01 by about 7 s, but the length of almost each note increased. This result means his finger movements became slower than in his initial performance. By contrast, the length of the rests decreased substantially, leading to faster tempo of his performance. Long rests between the notes indicated that a subject was looking for the next note or was hesitating because of a lack of confidence in playing. Reduction of rests was observed for almost all subjects after active or passive training, but was not evident if an exercise was not trained.

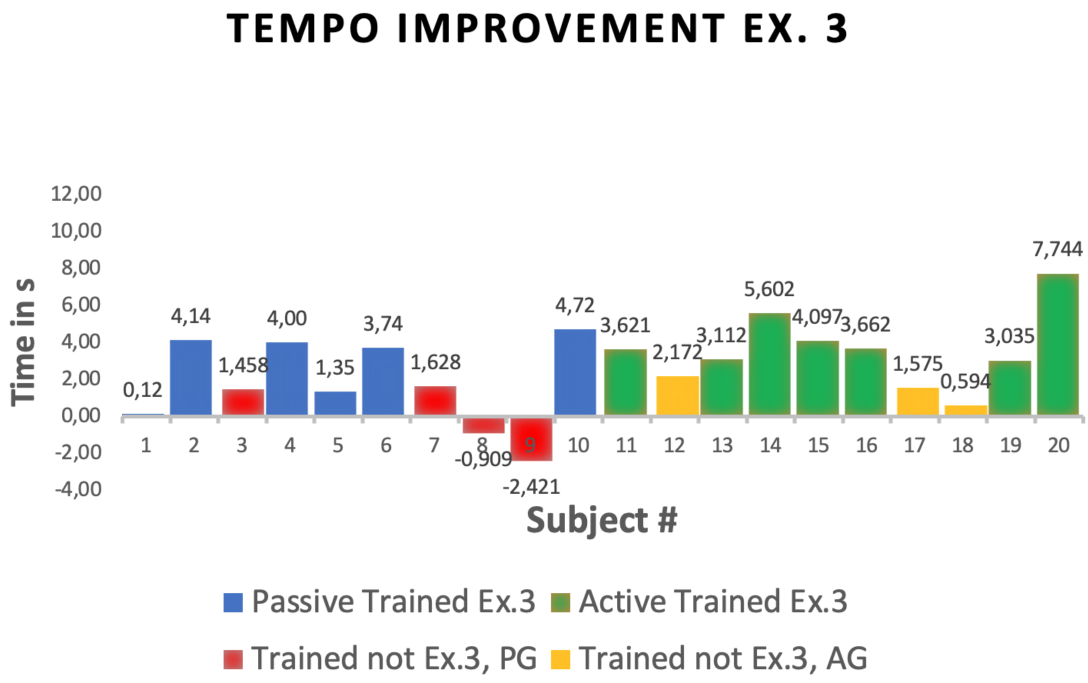


Figure 5.4: The bar chart illustrates the tempo improvements in seconds for Exercise 3 for each subject after the training

Tempo improvement				
Exercise #	**Mean**$_{before}$	**Mean**$_{after}$	**Imp. abs.**	**Imp. %**
1, PG	22,79	18,20	4,5	20,14
2, PG	22,95	18,45	4,5	19,61
3, PG	17,86	14,84	3,0	16,91
1, AG	23,14	17,86	5,3	22.82
2, AG	22,69	17,45	5,2	23,09
3, AG	20,75	16,34	4,4	21,25
1, PG w/o T	15,69	16,88	2,2	- 7,59
2, PG w/o T	22,87	21,08	1,8	7,83
3, PG w/o T	20,53	20,39	0,1	0,68
1, AG w/o T	20,39	20,68	- 0,3	-1,42
2, AG w/o T	23,71	21,44	1,4	9,57
3, AG w/o T	19,83	18,38	1,5	7,31

Table 5.2: Summary of the experimental results. The average values and the improvements for each group are displayed.

5.2 Accuracy

The accuracy was measured by counting the number of errors in a performance. If wrong notes were played, or if multiple keys were hit at once, it was considered a mistake.

The experimental results show no apparent difference in the number of mistakes between the active and the passive group. Figure ?? indicates that subjects who were trained improved significantly more than untrained subjects. Half of the subjects did not improve at all, mainly because most of them played in the initial recording errorfree. Four subjects performed worse after training, regardless of their group.

The passive group made 0,3 errors on average in the first round. After using HATS for 25 min, they performed worse. They deteriorated by 233.3 % making 1 error averagely in the second round. The active group could half their initial number of errors for the first exercise. From average 2 errors, they improved to exactly 1 error in the second round. The t-tests have shown that the differences in the number of errors made were not significant.

Figure 5.5: Improvement in performance of exercise 1 (errors in initial performance - errors made in final performance). Green colored bars indicate that subject did not train the exercise. Subjects 1 - 10 belong to the Passive Group,11 - 20 to the Active Group.

In contrast to exercise 1, the trained passive group could reduce the number of errors made, as shown in Figure 2. From 1.15 errors in the first round, they improved by 13.33 % and on average made only 1 error in the second round. Again a t-test showed, that the improvement was not significant.

The accuracy of the active group became worse in exercise 2. Initially, they made 0,71 errors on average. After practising the exercise, they made 1,29 mistakes in the second round.

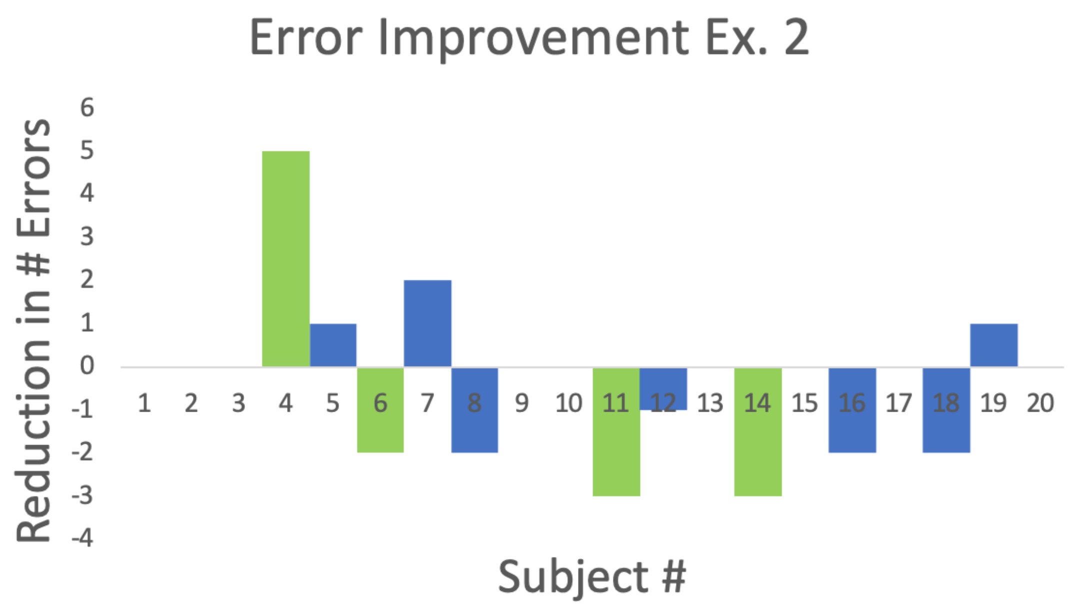


Figure 5.6: Improvement in performance of exercise 2 (errors in initial performance - errors made in final performance). Green colored bars indicate that subject did not train the exercise. Subjects 1 - 10 belong to the Passive Group,11 - 20 to the Active Group.

In the third exercise, even both groups became worse. The differences between the first and the second round were again minimal. The passive group deteriorated from an average of 0.68 to 1.33 errors, while the active group worsened going from 2 to 2.28 errors.

Most subjects made very few or no mistakes in their first performance, most likely because each exercise consists of a repetitive sequence. Interestingly, subjects who had made mistakes at the beginning reduced their mistakes in the second round, while subjects who had not made any mistakes, made mistakes. Unclean keystrokes caused the majority of mistakes. It was assumed that exercise 2 was the most difficult. However, most mistakes were surprisingly made in exercise 3.

The results show no significant differences between subjects, who trained an exercise, and subjects who did not train the same exercise. As in the above paragraphs, no tendency for improvement or deterioration was observed.

Untrained subjects of the passive worsened in the second round in exercise 1, and 3, but could improve in exercise 2. The deterioration in exercise 3 by 1.5 errors was even rated as marginally significant by a t-test. Interestingly, for each exercise, untrained subjects of the active group deteriorated in the second round compared to their initial performance. In exercise 2, they made on average 2 more mistakes than in the first round, which was the largest difference between the initial and final values compared to all other cases. The t-test showed again that the differences were not significant.

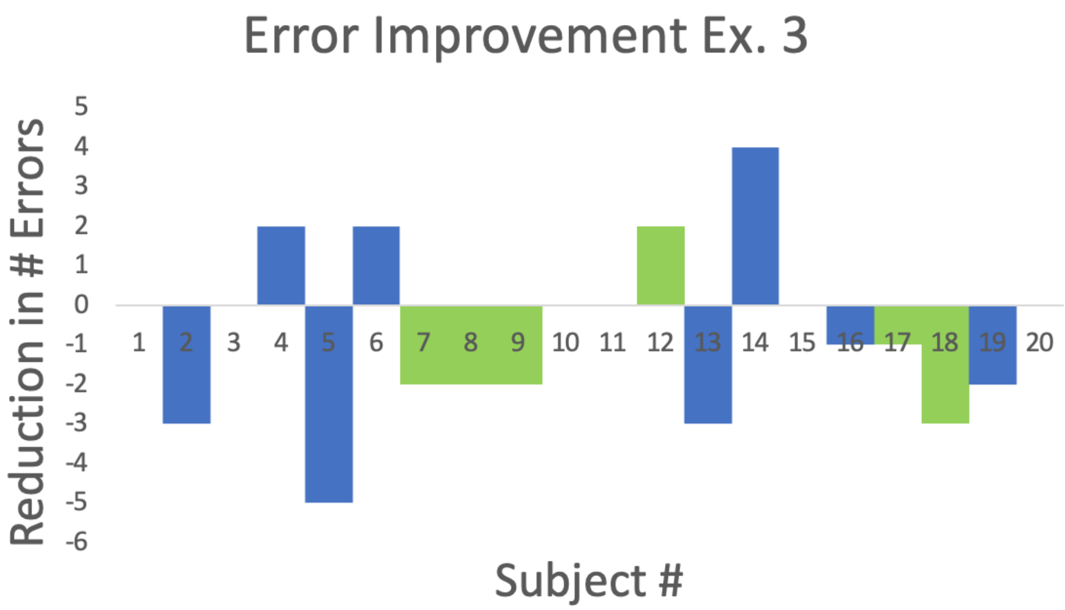


Figure 5.7: Improvement in performance of exercise 3 (errors in initial performance - errors made in final performance). Green colored bars indicate that subject did not train the exercise. Subjects 1 - 10 belong to the Passive Group,11 - 20 to the Active Group.

Reduction in # of errors			
Exercise #	**Mean**$_{before}$	**Mean**$_{after}$	**Imp. abs.**
1, PG	0,286	1	-0,714
2, PG	1,143	1	0,143
3, PG	0,667	1,333	-0,67
1, AG	2	1,167	0,833
2, AG	0,714	1,286	-0,572
3, AG	2	2,286	0,286
1, PG w/o T	1,333	2	-0,667
2, PG w/o T	1,667	0,667	1
3, PG w/o T	1	2,5	-1,5
1, AG w/o T	0,5	1	- 0,5
2, AG w/o T	0,667	2,667	-2
3, AG w/o T	2,333	3	-0,667

Table 5.3: Summary of the experimental results. The average values and the improvements for each group are displayed.

Accuracy - t-Tests: Paired Two Sample for Means, P(T<=t) two-tail				
Ex. #	Passive Group	Active Group	Passive Group w/o T	Active Group w/o T
1	$p < 0,40$	$p < 0,58$	$p < 0,64$	$p < 0,40$
2	$p < 0,77$	$p < 0,24$	$p < 0,68$	$p < 0,19$
3	$p < 0,59$	$p < 0,75$	$p < 0,058\ (MS)$	$p < 0,70$

Table 5.4: Pair-wise t-test results for comparisons of reductions in errors. P-values for each group and exercise are given. Significance is stated as significant (S), if p < 0.05, marginally significant (MS), if 0.05 < p < 0.075 and not significant, if not further specified.

5.3 Evenness

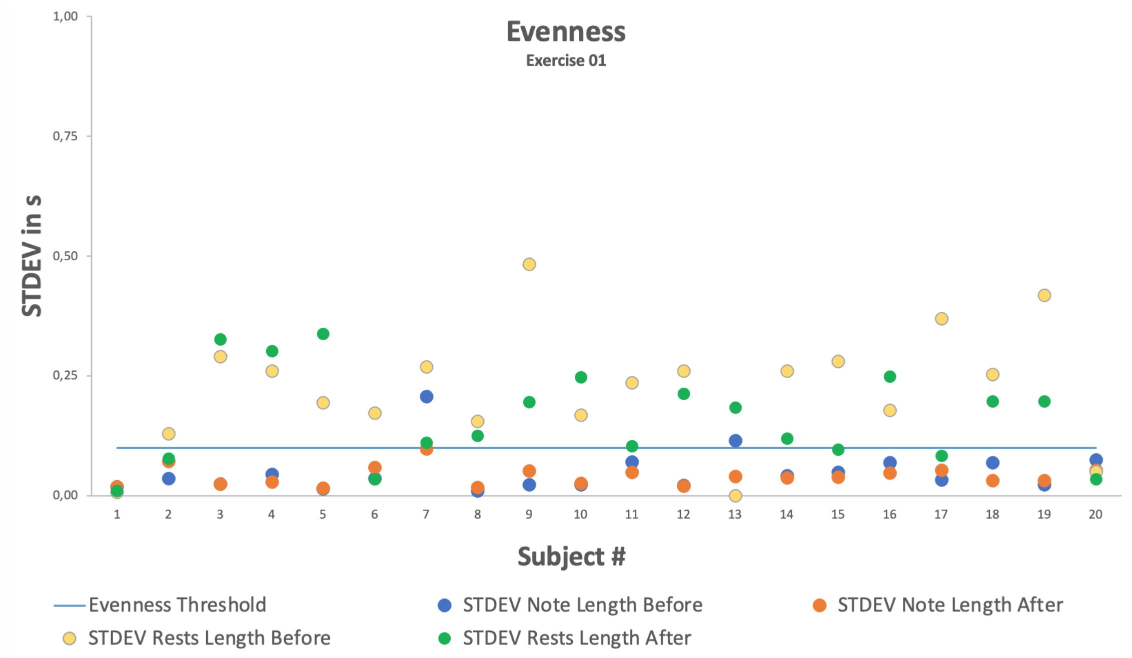


Figure 5.8: Evenness-chart Exercise 01. The standard deviation in s from the nominal value (See 4.1 and 4.2) is displayed. Subjects 1 - 10 belong to the Passive Group, 11 - 20 to the Active Group. Subjects 1, 5, 10 and 13, 16, 19, 20 did not train this exercise.

The scatter chart (5.8) displays the standard deviation of note length and rest length for Exercise 01, before and after training. The evenness threshold was defined as a standard deviation of 0,1 s. No scientific studies have been carried out to determine the length of time at which the unevenness of note delays is detectable. Therefore, the threshold value for noticing slight variations between note lengths was determined according to personal perception. All performances, whether before or after training, for which the deviation of notes and rests was below the threshold were considered to be even. In contrast, performances where one of them was above the threshold were uneven. The value was set as a form of error tolerance, as it is almost impossible to play the same length for every note. It was not intended for the rests, as it is easy to play a sequence of notes legato (i.e. without pauses between the notes). However, the results showed that the rest lengths were the main reason subjects did not play evenly.

Only in two out of 40 performances of exercise 1 was the note length outside the tolerance interval. In 35 of 40 performances, the standard deviation for rests before, after or both was above the evenness threshold. Seventeen of the 20 performances before training were uneven; after the training, 15 remained uneven. The reason was relatively simple: almost all subjects focussed mainly on the tempo of their performance, especially in the final round, when they were aiming to improve as much as possible.

By trying to play the exercises as quickly as possible, most subjects played the easy parts of a sequence fast and without rests. For more challenging parts, playing was often interrupted and the right notes were searched for, resulting in longer rests and thus larger standard deviations and higher variances. These dynamics can be seen in Fig. 4.8 regarding rest lengths; the peaks follow a pattern corresponding to the difficult part at the beginning of a sequence, where the hand must transpose to a higher note. Almost every t-test result (see 4.4) showed that the difference in the means was insignificant for both note length and rest length.

If only note length is examined, there is no clear trend in one direction or another. Generally, all performances of exercise 1 were even both before and after training. Some subjects were able to reduce the deviation in their note lengths; others increased them. There was no significant difference in the group means before and after training, for either group, as the t-tests indicated.

The distribution of pause lengths indicates a clear development. Nearly all the subjects who deteriorated did not train for the exercises, which meant they hesitated often and had to think about what key to strike next. By contrast, the trained subjects improved noticeably, regardless of whether they had trained actively or passively. The performance in the final round usually decreased the standard deviation of rest length. After training, most participants were able to play with more confidence and less hesitation, as mentioned in section 5.1. Hence, the total length of individual rests in a performance decreased. Because negative values in rest length are not possible, and zero was selected as nominal value, a decrease in the total length of individual rests always results in a decrease in the standard deviation.

Although differences were observed, two-tailed paired t-tests almost always showed that the differences were not significant. The only exception was the case of the active group with training on exercise 01.

In Figure 4.13, a similar trend is evident as in the first diagram. Again, uneven performances were mainly caused by long rests between notes, and the deviation of note length was generally below the threshold. Five subjects showed poorer performance compared to their initial rest-length deviation values; three of them did not train for this exercise.

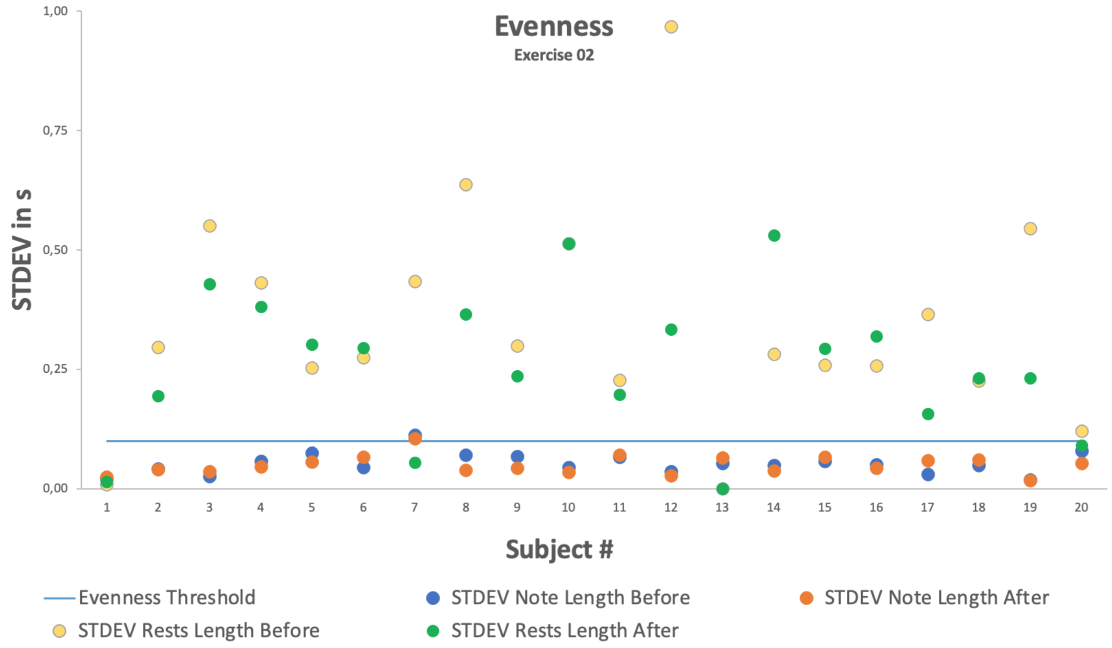


Figure 5.9: Evenness-chart Exercise 02. Subjects 1 - 10 belong to the Passive Group, 11 - 20 to the Active Group. Subjects 2, 4, 6 and 11, 14, 15 did not train Exercise 02.

In the scatter diagram 5.9, one can observe a similar trend like in the first diagram. Again, uneven performances were mainly caused by long rests between notes, while the deviation of note length is almost always below the threshold. Five subjects have deteriorated compared to their initial rests lengths deviation value; three of them were among the subjects who did not train this exercise.

Figure 5.10: Evenness-chart Exercise 03. Subjects 1 - 10 belong to the Passive Group, 11 - 20 to the Active Group. Subjects 3, 7, 8, 9 and 12, 17, 18 did not train Exercise 03.

t-Test: Paired Two Sample for Means, P(T<=t) two-tail				
Ex. #	**Passive Group**	**Active Group**	**Passive Group w/o T**	**Active Group w/o T**
1, NL	$p < 0,823$	$p < 0,302$	$p < 0,346$	$p < 0,208$
2, NL	$p < 0,105$	$p < 0,88$	$p < 0,804$	$p < 0,967$
3, NL	$p < 0,34$	$p < 0,55$	$p < 0,28$	$p < 0,13$
1, RL	$p < 0,11$	$p < 0,012\,(S)$	$p < 0,206$	$p < 0,966$
2, RL	$p < 0,113$	$p < 0,139$	$p < 0,340$	$p < 0,423$
3, RL	$p < 0,53$	$p < 0,107$	$p < 0,192$	$p < 0,132$

Table 5.5: Pair-wise t-test results for comparisons of evenness improvements. P-values for each training and exercise are given. No results were significant except one which is stated as (S). STDEV Notes Lengths is stated as NL, while STDEV Rests Lengths is stated as RL

5.4 Post-experimental Questionaire

After the experiment, the subjects were asked about their impressions of the training method. The questions for the passive group focussed on the HATS. Eight of the 10 subjects felt that the glove was comfortable and not restricting. One subject reported that it did not inconvenience him but he would not wear it for a longer time. One subject said that HATS was rather restricting as he feared damaging the electronics and thus did not want to move his hand unnecessarily.

When asked whether the vibrations were disturbing, no subjects answered affirmatively. All reported that they sensed the vibrations, but as soon as they started to answer the IQ test the vibrations became almost imperceptible, except during short intermittent breaks when they were not fully focused on the IQ task. Seven of the 10 subjects reported that they felt the stepwise increasing tempo of the vibrations had a positive effect on their performance. Two could not assess whether it had any positive effect. One subject reported that the speed of the glove was much faster than he could ever play; he said that the short intervals meant his fingers felt the vibrations less than they would have if the glove had been slower.

None of the subjects felt that their hand was somehow numb or exhausted after tactile stimulation. Three even noticed that the blood circulation in the fingers increased and the fingers felt more flexible. Eight subjects said that they would use HATS if they were to play the piano and the glove was more developed. Two subjects believed that HATS added no real value.

The members of the active group were asked how exhausting the exercises were. They mostly found them highly exhausting; on a scale of 1–10, they usually chose scores between 8 and 10. This was mainly because no subjects had practised regularly for the last five years, but had now just practised for 50 min at once.

When asked if they would perform technical exercises to improve their technique if they were playing the piano, five subjects said they would not. They said that practising the exercises was boring, undemanding and felt like ‘assembly line work’. They instead would play real piano pieces. The other five subjects said that they probably would practise technical exercises.

6. Discussion

In an experiment, improvements of the participants' finger dexterity after active and passive training were tested. Finger dexterity is the ability to play a sequence of notes on the piano at a fast pace while touching the key accurately and evenly. It was hypothesised that passive haptic training influences finger dexterity positively, that passive training is less effective than active training and that passive haptic training does not impact the general finger dexterity.

The results showed that the tempo of playing technical exercises increased significantly. On average, the time needed to complete an exercise decreased by about 20 %, if subjects trained it either actively or passively. However, there were no significant accuracy improvements. Participants deteriorated and improved after training, so there was no clear tendency, how training influences accuracy. The results of the evenness analysis showed that training did not influence note lengths, but rests lengths between notes decreased significantly. There were no significant differences in tempo, accuracy and evenness between the first and last performance of participants when they did not practice the exercise in between.

The results support the hypothesis that dexterity in terms of tempo can be improved passively and that it is also less effective than actively trained finger dexterity over the same period. Although the subjects generally improved on the untrained exercises, passive training did not appear to improve general dexterity; the t-tests showed the improvement was insignificant. Moreover, a substantial part of the improvement arose from the piano piece being played relatively fluently in the second round because it was already partially memorised. Subjects who played at a fast tempo initially barely improved after training.

Closer examination indicates that the improvement in tempo occurred because fewer rests were made between the notes. In the previous section, Figure 5.3 illustrates, that the time needed to play trough an exercise only reduced because the length of the rests decreased. In the faster second run, the subject's fingers stroked the keys even slower. This phenomenon could be observed for almost every subject who improved. This allows the assumption that the subjects intuitively knew when to play which finger. When the score required the hand to shift, most subjects hesitated again, leading to a increase of pause lengths.

Furthermore, the actual tempo of playing did not improve noticeably, and sometimes it even worsened slightly. The same could be observed for active training. Active and passive training help to play more fluently and with less hesitation, but do not help to improve the actual tempo of stroking the key, at least not in the short term. Therefore, no change could be observed in the tempo of untrained exercises. The participants could not remember fingerings better without training, sometimes even worse.

Huang et al. found that subjects played piano songs more flawlessly and with less hesitation after learning the piano song with tactile stimulation [6]. The same observation was made in this thesis' experiment. In contrast to MMT or PT, the fingers were not mapped each to one key on the keyboard, requiring hand shifts when playing the exercises. During these shifts, subjects hesitated.

Such hesitation indicates a limitation of passive training of piano playing through vibrotactile stimulation. It seems that the method is particularly effective in learning and remembering fingerings, but not for executing more complex hand movements. This point is supported by the fact that subjects took less time between notes deciding which finger should press the key than they had before training. Moreover, subjects who were already able to play confidently in the beginning and had a good starting performance barely improved after training. They could already repeat the notes assuredly in the beginning.

Regarding hand shifts, the active group performed noticeably better than the passive group. The active group showed more certain improvements in tempo and accuracy than the passive group.

However, the data did not support an significant improvement in accuracy for both groups. Usually, the accuracy worsened, mainly because participants wanted to improve as noticeable as possible and consequently played as fast as possible in the second round at the expense of accuracy. Most of the counted errors were caused by unclean keystrokes (i.e. multiple keys were accidentally hit at once). Lack of control of the fingers often results in unclean keystrokes, and especially playing too fast leads to loss of control, which explains that almost every group worsened on average. It should also be noted that the number of errors was low from the beginning, so there was not much space for improvement. The reason that active training did not improve accuracy is that some participants expected the most of themselves and played faster as they could control, leading to a higher number of errors compared to the initial performance.

It was concluded that HATS does not affect accuracy. After all, tactile stimulation of the back of the fingers does not influence which key is pressed or how.

Regarding changes in evenness, the results indicated a noticeable improvement after training. However, this applied only to the rests between the notes; the note length barely changed. The t-test showed the differences to be not significant.

Huang et al. stated that subjects who learned piano pieces through tactile stimulation performed poorly on rhythm [6]. In this experiment, even when exercises did not include difficult rhythms but instead, each note was to be played for equal periods, similar observations were made. Subjects in the passive group did not perform as well as subjects in the active group regarding note length and evenness of performance. These points are related to rhythm, which requires precise control over note and pause lengths.

The bottom line is, the results were similar to the observations of MMT. Hence, the first hypothesis was rejected. Although one could certainly try to force the data into a kind of confirmation, since there are indeed observable improvements, the data are not necessarily a valid indicator of finger dexterity enhancement. This could be because the subjects learned the exercises passively, which made it easier for them to recall them and therefore play them more fluently.

It was evident that finger and hand coordination did not improve noticeably, which led to many notes being played imprecisely and thus to mistakes. There was no evidence that subjects had more control over playing more evenly. The results were not sufficient to establish a real improvement in finger dexterity. Hence, passive haptic training affected finger dexterity only by helping the subject to learn and recall a piece, which improved their fluency in playing the piece.

The other two premises of the hypothesis were confirmed. The experimental results indicated that on average, the active group improved more than the passive group on almost all exercises in all categories. However, it was assumed that the gap between both groups would be much more significant. The active group performed slightly more poorly than had been expected, whereas the passive group exceeded expectations, mainly by playing faster than expected.

There were no effects on general finger dexterity. Regardless of the group, the findings did not indicate improved control over finger coordination or better performance of untrained exercises. Overall, general dexterity is not trained by HATS, and the data did not indicate a positive influence on accuracy and evenness.

However, other discoveries were made which need further investigation. It has been shown that subjects older than 50 years struggled with active learning of the exercises initially. After passive training, they improved almost as much as did younger subjects. It appears that they preferred passive rather than active learning of motor skills. Only two subjects were older than 50 in this study. Therefore, the assumption is not meaningful and further research with older participants is required to investigate active versus passive haptic learning of motor skills.

After questioning the participants, it became clear that the active fast practice of scales is strenuous for participants who lack piano experience. In comparison, the passive group did not feel that their hand was exhausted. Nevertheless, they had improved almost as much as the active group. The passive exercise system could be used with small adjustments so that beginners who reach the limits of their endurance with untrained hands can continue to practise without overstraining the hand and risking injury. In this way, beginners could learn more pieces in a short time and make progress. The effectiveness of combined passive and active learning could be examined over a longer period to make more precise conclusions.

In this thesis, the HATS system used the method of stepwise increasing tempo. Although the majority of the subjects felt it had an additional positive effect by increasing the speed of the vibrations, there is no comparison with a haptic system without increasing tempo, where this is confirmed. In the future, a study is planned to examine, if the duration of vibration affects the tempo of playing scales. Passive haptic training with stepwise increasing speed will be compared, to passive haptic training with no tempo changes.

7. Conclusion

In this thesis, the impact of passive haptic training on finger dexterity was examined, and additionally compared to active training of the same exercises, in order to estimate the effectiveness of passive training.

A passive haptic training system was developed, basing on the method of step-wise increasing tempo, which is used in piano practice to master difficult passages with a high pace. An experiment then evaluated the training system.

The results showed that the subjects could play more flawlessly and with less hesitation after training. However, the accuracy and the evenness of the performance did not improve significantly. Consequently, the central hypothesis, that passive haptic training impacts finger dexterity positively, is being rejected, since a mere improvement in tempo due to less hesitation was not considered sufficient to confirm a positive impact on finger dexterity.

The comparison between active and passive training revealed that passive and active training are almost equally effective. The hypothesis that active learning is more effective than passive learning was confirmed. Subjects who trained active always improved slightly more than subjects of the passive group, and had fewer problems with more complex hand movements, such as hand shifts.

For both the active and passive groups, no significant changes were found in comparison to the improvement of general finger dexterity. Therefore the last hypothesis that passive learning does not improve general finger dexterity was also confirmed.

The study reinforced observation from earlier studies that subjects could play with fewer hesitations after the training. It also shows a tendency that tactile stimulation of the fingers only is insufficient to learn piano songs, as sections requiring more complex hand movements did not improve. However, it has also been shown that passive training does not exhaust the hand at all, while active training for the same period of time puts much strain, particularly on the wrist.

It has been shown that HATS is not sufficient to train finger dexterity. It only affects finger dexterity in the way that passages are played less hesitantly because, after passive training, it seems easier to recall them. Accuracy and Evenness were not impacted significantly. However, a combination of active and passive training can be used to learn a piece with less active practice. In this way, the hand could be spared from injuries in the long run. More detailed studies are planned.

A. Appendix

The following pages contain the tables, which display all gathered data by the experiment. For each table applies:

- Subjects 1 - 10 are members of the passive group
- Subjects 11 - 20 are members of the active group.
- Table cells marked in blue indicate that the respective participant has not trained this exercise.

Technical Excercise 1

Subject-Nr.	Duration		Mistakes		STDEV Note Length		STDEV Rests Length	
	Before	After	Before	After	Before	After	Before	After
1	10,85	11,35	0	0	0,018	0,018	0,007	0,010
2	19,98	17,05	0	4	0,035	0,071	0,129	0,077
3	23,77	22,02	0	0	0,024	0,025	0,290	0,327
4	24,10	21,50	0	3	0,045	0,028	0,260	0,301
5	18,46	19,89	4	3	0,013	0,015	0,194	0,337
6	19,67	11,68	0	0	0,035	0,059	0,173	0,035
7	28,06	18,50	2	0	0,206	0,098	0,269	0,111
8	15,91	15,28	0	0	0,010	0,017	0,155	0,125
9	28,06	21,33	0	0	0,023	0,051	0,483	0,196
10	17,76	19,40	0	3	0,023	0,025	0,168	0,247
11	23,50	17,36	2	0	0,070	0,049	0,235	0,104
12	22,55	18,98	6	0	0,022	0,020	0,260	0,212
13	15,45	20,67	0	0	0,115	0,039	0,000	0,184
14	23,25	18,12	0	0	0,041	0,036	0,260	0,119
15	25,85	17,28	4	2	0,048	0,039	0,280	0,096
16	25,49	24,50	2	4	0,069	0,047	0,178	0,248
17	23,83	19,89	0	1	0,032	0,052	0,369	0,082
18	19,84	15,55	0	4	0,069	0,031	0,253	0,196
19	27,23	25,50	0	0	0,023	0,031	0,418	0,196
20	13,39	12,05	0	0	0,075	0,053	0,050	0,035

Technical Excercise 2

Subject-Nr.	Duration		Mistakes		STDEV Note Length		STDEV Rests Length	
	Before	After	Before	After	Before	After	Before	After
1	10,53	10,80	0	0	0,019	0,025	0,008	0,014
2	23,13	18,11	0	0	0,042	0,039	0,295	0,194
3	28,87	22,77	0	0	0,026	0,035	0,550	0,428
4	25,80	23,85	5	0	0,057	0,046	0,431	0,381
5	21,07	21,16	3	2	0,074	0,056	0,253	0,302
6	19,69	21,29	0	2	0,044	0,066	0,274	0,294
7	27,85	16,30	2	0	0,112	0,105	0,434	0,055
8	23,65	18,27	3	5	0,070	0,038	0,636	0,366
9	21,49	17,87	0	0	0,068	0,042	0,299	0,235
10	27,21	21,99	0	0	0,045	0,035	0,512	0,512
11	18,60	18,49	0	3	0,066	0,070	0,228	0,197
12	32,52	20,84	3	4	0,035	0,027	0,967	0,333
13	21,58	14,66	0	0	0,053	0,065	0,000	0,000
14	19,38	20,46	2	5	0,049	0,036	0,282	0,531
15	21,62	21,02	0	0	0,057	0,066	0,258	0,293
16	24,66	20,15	0	2	0,051	0,043	0,257	0,318
17	21,73	16,83	0	0	0,030	0,059	0,364	0,156
18	19,73	18,04	0	2	0,049	0,060	0,226	0,231
19	24,35	20,17	2	1	0,019	0,017	0,545	0,231
20	14,29	11,48	0	0	0,078	0,052	0,121	0,090

Technical Excercise 3

	Duration		Mistakes		STDEV Note Length		STDEV Rests Length	
Subject-Nr.	Before	After	Before	After	Before	After	Before	After
1	9,74	9,62	0	0	0,018	0,017	0,010	0,010
2	23,25	19,11	0	3	0,040	0,069	0,243	0,166
3	21,68	20,22	0	0	0,030	0,028	0,377	0,341
4	19,34	15,34	2	0	0,023	0,030	0,317	0,192
5	15,78	14,43	0	5	0,057	0,186	0,000	0,198
6	18,80	15,06	2	0	0,052	0,037	0,248	0,196
7	20,47	18,84	2	4	0,252	0,270	0,204	0,248
8	17,70	17,79	0	2	0,064	0,075	0,130	0,403
9	22,27	24,70	2	4	0,030	0,028	0,376	0,559
10	20,22	15,51	0	0	0,036	0,028	0,341	0,190
11	18,21	14,58	2	2	0,083	0,053	0,185	0,141
12	19,49	17,32	4	2	0,037	0,070	0,368	0,288
13	17,61	14,50	0	3	0,069	0,111	0,213	0,000
14	22,38	16,77	6	2	0,041	0,086	0,427	0,216
15	17,96	13,87	4	4	0,093	0,069	0,156	0,106
16	21,45	17,79	0	1	0,088	0,033	0,232	0,313
17	20,27	18,69	3	4	0,030	0,066	0,353	0,156
18	19,74	19,14	0	3	0,065	0,070	0,246	0,193
19	29,76	26,73	0	2	0,019	0,027	0,613	0,521
20	17,89	10,15	2	2	0,123	0,063	0,108	0,101

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