Let's Frets! Assisting Guitar Students During Practice via Capacitive Sensing

Karola Marky
Technical University of Darmstadt, Germany,
University of Glasgow, Scotland
karola.marky@glasgow.ac.uk

Andreas Weiß
Music School Schallkultur, Kaiserslautern, Germany
andreas.weiss@musikschule-schallkultur.de

Andrii Matviienko
Florian Brandherm
Technical University of Darmstadt, Germany

Sebastian Wolf
Martin Schmitz
Technical University of Darmstadt, Germany

Florian Krell
Florian Müller
Technical University of Darmstadt, Germany

Max Mühlhäuser
Thomas Kosch
Technical University of Darmstadt, Germany

Figure 1: We present *Let's Frets*, a modular guitar learning concept with three feedback modules: (1) visual indicators, (2) finger position capturing, and (3) a combination of both modules.

ABSTRACT

Learning a musical instrument requires regular exercise. However, students are often on their own during their practice sessions due to the limited time with their teachers, which increases the likelihood of mislearning playing techniques. To address this issue, we present *Let's Frets* - a modular guitar learning system that provides visual indicators and capturing of finger positions on a 3D-printed capacitive guitar fretboard. We based the design of *Let's Frets* on requirements collected through in-depth interviews with professional guitarists and teachers. In a user study (N=24), we evaluated the feedback modules of *Let's Frets* against fretboard charts. Our results show that visual indicators require the least time to realize new finger positions while a combination of visual indicators and position capturing yielded the highest playing accuracy. We conclude how *Let's Frets* enables independent practice sessions that can be translated to other musical instruments.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**.

KEYWORDS

musical instruments, support setup, capacitive sensing

ACM Reference Format:
Karola Marky, Andreas Weiß, Andrii Matviienko, Florian Brandherm, Sebastian Wolf, Martin Schmitz, Florian Krell, Florian Müller, Max Mühlhäuser, and Thomas Kosch. 2021. Let's Frets! Assisting Guitar Students During Practice via Capacitive Sensing. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3411764.3445595

CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445595

1 INTRODUCTION

The guitar is one of the most popular musical instruments among autodidacts that is easy to learn but difficult to master. Using both hands, one hand either strums or plucks strings while the fingers of the other hand simultaneously press the strings. Acquiring these skills that include a sense of rhythm and the agility to play the strings, which, in turn, require time-consuming training [11, 22, 36].

Guitar students practice alone the overwhelming majority of the time. Especially beginners struggle during practice sessions because the feedback options, such as direct feedback from a guitar teacher, are limited. Lessons can be costly, and teachers are only available at fixed times, resulting in incorrect movements or postures because lacking adequate and immediate feedback. Such incorrect movements or postures can be an issue for two reasons: First, they might be difficult and time-consuming to correct later. Second, the execution of these motions might lead to health problems (e.g., the "Repetitive Strain Injury" (RSI) syndrome [30]).

To mitigate these issues, technology-based concepts have been proposed in the literature and are available by commercial vendors. Each concept transforms the guitar into a smart object by additional components, such as projectors [23, 24], actuators [19], or light indicators [10, 35, 38]. While these setups enhance the practice experience, they also possess limitations. Actuators can impact the components of an instrument. Projections or light indicators alone cannot ensure that students indeed place their fingers in the correct position on the musical instrument.

In this paper, we present design requirements as well as a prototype implementation of a smart guitar that mitigates the aforementioned concerns. We first report an interview study with ten experienced guitar professionals and teachers. Based on the study, we list requirements for smart guitars that support practicing new skills. To realize the requirements, we propose *Let's Frets* – a modular guitar practicing concept that combines visual indicators, feedback about finger positions on the fretboard, and a dedicated practice software (see Figure 1). To realize the finger position capturing, we integrated 3D-printed capacitive sensors into the fretboard. Thus, our practice setup does not require any external components, and the guitar's haptics are not altered since the finger positions are captured by the fretboard. The finger position capturing is visualized for the student via an app on a smartphone, while visual feedback can be displayed on the fretboard or the smartphone app.

To realize *Let's Frets*, we discussed the resulting requirements with guitar professionals and teachers and designed a prototype electric guitar in an iterative process. We evaluated the practice of simple guitar chords with our proposed concept in a user study with 24 participants. We compared assistance by visual indicators, finger position capturing, and the combination of both to classic fretboard charts as a baseline. Through this study, we demonstrated the usability of *Let's Frets*. Our results show that visual indicators helped students play given chords faster while capacitive sensing combined with visual indicators showed the least number of errors. We are confident that the presented sensing technology of *Let's Frets* is not limited to guitars and contribute options to integrate *Let's Frets* into other musical instruments.

CONTRIBUTION STATEMENT

The contribution of this paper is threefold:

(1) We elaborate on the design of smart guitars for practicing purposes through qualitative interviews with aspiring guitar professionals and teachers.
(2) Then, we present the implementation of a smart guitar prototype that utilizes visual indicators and capacitive sensing to enhance the practice experience of guitar students.
(3) Finally, we conduct a study to investigate the usability and efficiency of the smart guitar. We conclude with a discussion of how our approach can be used to develop and integrate novel assistive systems for other musical instruments.

2 BACKGROUND AND RELATED WORK

Several setups for augmented guitars and other string-based musical instruments have been proposed in the literature or are available from commercial providers. Within this section, we first give an overview of *traditional guitar notation*. Then, we provide an overview on *audio analysis*, setups based on *visual indicators* and *finger detection*. Finally, we detail related works that describe *support setups for other musical instruments*.

2.1 Traditional Guitar Notation

Besides classical sheet music, guitar players use tabulators (tabs) to write down music. Tabs are visual representations of the guitar strings. A line represents each string, and a number noted on the line denotes the fret in which the finger should be placed. A zero denotes that the respective string is strummed without being pressed. Fretboard charts depict the finger placements of chords independent of time and rhythm [13]. Those are similar to tabs, but instead of numbers, the frets are separated visually, and a black dot represents the finger target. Tabs and fretboard charts are traditional methods used for learning new chords, scales, or melodies.

2.2 Audio Analysis

Several systems aim to support the acquirement of guitar skills based on audio analysis [1, 3, 26, 44]. This forms a possible solution to determine the student's finger position indirectly. The commercial system Rocksmith [17] is based on audio analysis and provides visualization on a TV. While such setups can be used with any guitar, audio analysis has limitations. First, not all playable tones have an unambiguous position on the fretboard. Depending on its scale, a guitar has about 150 possible finger positions but can only produce 45 different tones. Second, it is not possible to receive feedback without strumming the strings. Finally, even if the played tone sounds correct, the fingers or fingertips might be in a non-ideal position. Therefore, finger position estimation by audio is not sufficient.

2.3 Visual Indicators

Several guitar setups with integrated lights as visual indicators in the fretboard are available commercially, such as the GTar [16] or FretLight [38]. The usage of lights as visual indicators has been investigated in several works. Lights are beneficial for beginners to learn finger placements, but there is no long-term benefit over traditional notation [20]. The finger targets can also be projected on the fretboard or visualized by augmented reality [23, 25].

Other setups use a combination of screen and camera to provide visual feedback [21]. This can be realized by tracking the guitar neck and the fingers of the students with markers. Because the students have to look at a screen, their view of the finger targets is inverted. Thus, similarly to traditional depictions on paper, a constant spatial mapping between the screen and the real world is required. Motogawa *et al.* extended the setups mentioned above by adding a 3D-model of the ideal hand posture to the camera image [27]. Finally, Harrison *et al.* simplified that guitar by substituting the strings with buttons that trigger chords to support learning-disabled musicians [14].

2.4 Finger Detection

Visual indication alone is not sufficient for learning new finger positions because the students have to make sure that they indeed placed their fingers correctly. Furthermore, it is difficult to adjust the visual output to the student's speed and learning curve. As mentioned above, existing setups used optical markers which are placed on the student's fingernails to detect the finger positions with an external camera [5, 21, 27] or augmented reality [31]. The captured data was used to overlay the camera image with target finger positions and directions.

The system *EMGuitar* uses electromyography to assess the student's finger postures on the guitar [19]. Electromyography captures the electrical activity that is produced by a muscle. Therefore, students wear electrodes around their arm that captures muscular activity. Software adjusts the tempo of displayed chords such that the student can play without interruptions. However, this requires setup time to put electrodes on the student's arm.

Shin *et al.* proposes a guitar setup that combines integrated LEDs, piezo sensors, and microcontrollers [35]. They use different light colors for the different fingers and an application to provide feedback. The feedback is limited to the duration of a chord or tone and the finger's position on the fretboard. The setup of Shin *et al.* is similar to *Let's Frets*, however, Shin *et al.* placed a PCB below the fretboard changing the haptics of the guitar. Furthermore, the combination of visual indication and finger position capturing has not been evaluated with users.

2.5 Setups for Other Musical Instruments

One stream of research specifically investigated methods for visualizing, which notes to play on pianos. The notes can be visualized by vertical bars on a screen that float towards the keys of a piano depiction. The length of a bar represents the length of a tone. A commonly used commercial software for that is Synthesia [39]. Compared to music notation on sheets, the bar representation is more intuitive and supports beginners [32]. This representation can also be projected on the piano or a surface above it to have a better connection to the physical keys [29, 32, 43]. Another option to highlight the keys is using augmented reality via mobile devices [9], or head-mounted displays [25].

Projection surfaces, however, need to be placed on top of the piano, restricting these to specific piano types. Another option is projecting the connection between the tone denoted by sheet music, and the pressed piano key [40] visualizing the hands of another person that plays shifted by one octave [42]. Besides music notation, the placement and choice of fingers are crucial for piano playing. Related work presented a haptic glove that teaches the fingering for playing the piano [15]. Finally, Karolus *et al.* [18] investigated how muscular activity can be utilized as an additional playing modality. In a showcase scenario, different pressing strengths of thumb were detected to modulate a pitch wheel as soon as the player pressed with their thumb on a key.

Finally, past research has looked into the augmentation of violins. The body posture is important for playing the violin. The setup MusicJacket is a jacket for teaching body posture and the bowing techniques via vibrotactile feedback [41]. The students' motions are captured by sensors and corrected by vibration motors on the upper body. Past research also looked at methods to augment the violin's fingerboard. This can be realized by resistive sensors [12, 28] or based on motion sensors [8].

3 EXPERT STUDY AND REQUIREMENTS

To collect requirements for a guitar setup that support the acquirement of new skills, we conducted in-depth interviews with ten guitar teachers and experienced guitar players. The interviews were semi-structured. Hence, we had a common set of questions for participants and the opportunity to investigate their answers in more depth. After discussing the interview questions with three authors of the paper, we conducted a pilot interview with one guitar teacher. We used the pilot interview to improve the clarity of our questions and to adapt the wording.

3.1 Interview Procedure

The interview procedure was as follows and took , on average, one hour:

3.1.1 Welcome and Consent. First, the examiner welcomed the participants and provided them with an informed consent sheet. Because the interview was conducted online, we recorded the consent expressed by the participants. This audio file was kept separate from the interview recordings.

3.1.2 Demographics. We commenced the interview with demographic questions asking for the participants' age, gender, education, and occupation. Next, we asked them about their experiences with musical instruments. In particular, we asked which musical instruments they play, which kind of guitar they play (electric, classical, ukulele, bass), and for how long they played the guitar. Then, we asked how long they practice per week. The experts were asked to rate their theoretical knowledge and practical skills on the guitar and how they acquired their knowledge and skills. If the participant was a guitar teacher, we asked how long they have been teaching and how they teach (individual students, classes, remote).

3.1.3 Teaching Materials. To get started with the semi-structured interview, we asked the participants to tell us about their last guitar lesson or practice session. Based on that, we asked the teachers which materials they use for teaching the guitar and the professionals which materials they used when learning the guitar. For each material, we asked them about the benefits and drawbacks.

3.1.4 Technology and Software. In this part, we focused the interview more specifically on technical devices and software that the guitar professionals and teachers use for practice and teaching.

3.1.5 Assisting Technologies. In the final part of the interview, we talked about possible guitar augmentation and modifications. We asked the participants about predominant problems when learning the guitar and possible means to address these. For this, we focused on *which* problem could be solved by an assisting technology but not on *how* this could be realized.

3.2 Participants

To collect the requirements for *Let's Frets*, we recruited ten guitar experts, one of them identified as female. The participants had different professional musical occupations, such as students majoring in music with a focus on guitar ($N = 3$), experienced guitar players ($N = 2$), guitar teachers ($N = 4$), and retired teachers of music ($N = 1$). All of the participants majored in guitar playing and had between two and 50 years ($M = 27$, $SD = 16$) of experience playing an acoustic and electrical guitar professionally. Six experts regularly gave guitar lessons and had between four to 1000 graduate students.

3.3 Data Analysis

Before the analysis, we transcribed all interview recordings. Then, we followed an open coding approach for analysis with the following research questions:

RQ1: Which problems were experienced during practice?
RQ2: What kind of materials were used for practicing?
RQ3: What kind of technical devices were used to support learning?
RQ4: What kind of software was used to support learning?
RQ5: What are the requirements and limitations for assistive systems?

Based on our research questions and the transcripts, we developed a codebook with five code categories: 1) experienced problems, 2) learning materials, 3) technical devices, 4) software, and 5) properties of assistive systems. The codebook contained a total of twelve codes. Based on the codebook, two authors of the paper coded all transcripts independently with an agreement rate of 89.19%. For the inter-rater reliability, we calculated Cohen's κ, which is 0.857, referring to an almost perfect agreement of the coders [7]. Inclusive codings were discussed in a meeting, and final code allocations were agreed on.

3.4 Interview Results

In this section, we present the results of the interview study. We report the results based on the five categories detailed above with an emphasis on the properties of assistive systems.

3.4.1 Experienced Problems. When we asked the participants about problems during guitar practice, they reported four specific aspects: 1) motoric, 2) motivation, 3) limitations, and 4) technical aspects.

Motoric problems were connected to the physical properties of guitar students, such as hand size and force transmission. Motivational problems were twofold. First, they were connected to the motivation to practice at home. Second, they were connected to the motivation of learning a particular technique.

Limitations refer to aspects that limit teaching effectiveness, such as temporal constraints or room availability. Furthermore, some teachers reported that their students do not have access to an instrument for practicing at home. Finally, technical aspects mean that existing materials or technologies also possess limitations. For instance, before learning the actual instrumental, the student also has to learn music notation and general aspects about the instrument, such as requirements for the generation of correct sounds. For the guitar, this means pressing the string with enough force close to the fret.

3.4.2 Learning materials. As learning materials, the guitarists reported using songbooks, sheet music, fretboard charts, tabs, and individually composed exercises. Most teachers tailored the learning materials to individual students except for those who taught classes with more than two students. When asked for limitations of the teaching materials, the participants named that an initial training period is needed to learn notations. Even if fretboard charts and tabs denote finger placements, the students have to translate them to the guitar fretboard, which is challenging for beginners. As main challenge, the participants named that the materials are separate from the guitar. Consequently, the students have to switch their visual attention between the guitar and the materials.

3.4.3 Technical devices. When asked for technical devices, almost all guitarists reported using metronomes and guitar tuning devices. Some also used loopers and reported to use recording devices to show the students how they play. Metronomes were perceived quite differently. On the one hand, the participants stated that it is important to improve playing accuracy. On the other hand, it should not be used too frequently because students might develop dependence. Another negative aspect was the artificial sound of the metronome. One guitar teacher used drum-sounds instead to create a more realistic feeling of playing in a band.

3.4.4 Software. As software, the teachers used music players, video calling software for remote lessons, and apps for tuning. Several limitations of video calling software were mentioned. Teachers had difficulties in 1) judging the students' actions and 2) demonstrating their actions on the guitar. The main problems were the limitation to a two-dimensional image that requires perceptual mappings meaning the students have to transform the teacher's actions in their minds.

3.4.5 Properties of assistive systems. When asked for the properties of assistive systems, most participants mentioned that they should reduce the cognitive load for beginners. When starting to learn the guitar, the students have to learn music notation and acquire playing skills. The depictions of chords, e.g., by fretboard charts, require a mapping from the chart to the guitar fretboard. This separation makes it difficult for beginners to learn finger placements.

In this scope, the importance of finger placement was stressed by almost all participants. First, students should receive feedback on whether they placed their fingers correctly on the fretboard. This should include the pressing of strings since they might accidentally touch strings. Furthermore, new guitar students particularly struggle in placing the fingers correctly within the frets. When placing the finger, it is important to place it as close to the fret as possible.

Another aspect related to finger placement is the ambiguity of placing chords. For instance, for an e-minor chord, only two fingers are required. Hence, the chord can be played with the index and middle fingers or middle and ring fingers. The choice of fingers follows general rules but can also be dependent on preceding or subsiding chords. These aspects also have to be considered while practicing. The participants stated that beginners should be supported regarding their finger choice. Finally, the applied force is

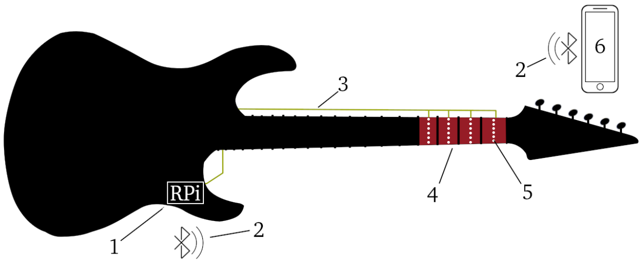


Figure 2: Schematic of *Let's Frets*. A Raspberry Pi (1) communicates via Bluetooth (2) with a smartphone app (6). The conductive frets (4) and LEDs (5) are connected via cables to the Raspberry Pi.

crucial. Beginners tend to apply too much force, which can lead to health problems and might impact the fluidity of playing.

The skillset of beginners changes rapidly. Thus, a support system should be adjustable to that. Participants stated that students have difficulties interpreting music notation in the beginning, while later on, these difficulties vanish. Based on that, participants wished to adjust a learning setup or instruments to students' level.

Two further important aspects mentioned by most participants were related to the haptics of the instruments and cost. First, a learning setup should support the students ideally without changing any haptics from the guitar and without the need for additional components. Second, learning setups should be cost-effective.

3.5 Requirements

Based on the interview results, we distill the following requirements for guitars that supported the acquirement of new skills focusing on beginners.

- **No haptic impact:** Learning guitar setups should have similar or identical haptics to a normal guitar.
- **Integrated guidance:** For beginners, guidance about finger placement should be integrated into the instrument to facilitate a start without detailed knowledge about music notation.
- **Guidance for finger choice:** Guidance about finger placements should include a choice of fingers.
- **Adjustability:** Learning guitar setups should be adjustable to the students' skills.
- **Finger feedback (fret):** Students should receive feedback about their finger placement on the fretboard.
- **Finger feedback (string):** Students should receive feedback about accidentally strummed strings.
- **Finger feedback (force):** Students should receive feedback about the force applied when pressing the string, such that they can adjust it to the required level.
- **Cost effectiveness:** Learning setups should be cost-effective.

4 THE SMART GUITAR FEEDBACK SYSTEM

In this section, we describe *Let's Frets*. We detail its setup and explain the integrated assistive feedback modules and their functionality. We published the 3D models and the source code of *Let's Frets* to foster future research developments in the community[1].

4.1 General Setup

Let's Frets consists of two components: a smart guitar and a mobile app. For realizing the smart guitar, we used an electronic guitar as a basis. The smart guitar provides guidance through visual indicators and can capture the fingers of the guitarist. Detailed information about that is given below. We modified the fretboard of a regular guitar to enable guidance and feedback without altering the haptic of the guitar (i.e., fulfilling the requirement *no haptic impact*). For our prototype, we removed the fretboard from the first four frets and replaced it with our developed components. As on-board controller, we used a Raspberry Pi (see Figure 2) that communicates with the mobile app via Bluetooth.

4.2 Visual Guidance

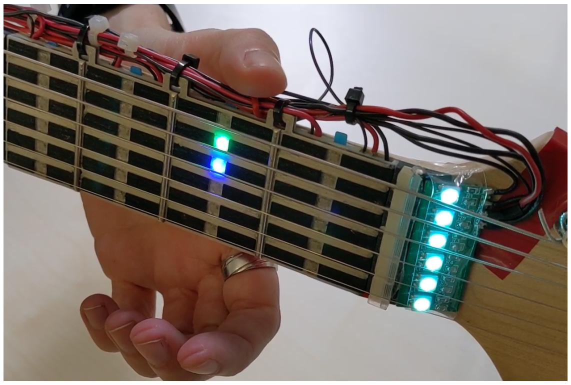
To realize the requirements *integrated guidance* and *guidance for finger choice*, we integrated RGB-LEDs into the fretboard (see Figure 3a). The RGB-LEDs are visible through a transparent layer of PLA and are placed in the center of each fret. A separate set of LEDs was placed above the nut of the guitar to indicate the strings that the student has to strum. The color of the LEDs is customizable and indicates where to place the fingers. Different colors can either be used to assign specific fingers to positions or to communicate specific playing styles (*e.g.,* bending, hammer-on, pull-off, or vibrato). In the app, students and teachers can store chords, finger positions, and sequences of those. Based on that, the app provides a mode in which the students can adjust how long they wish to practice each sequence.

4.3 Capturing Finger Positions

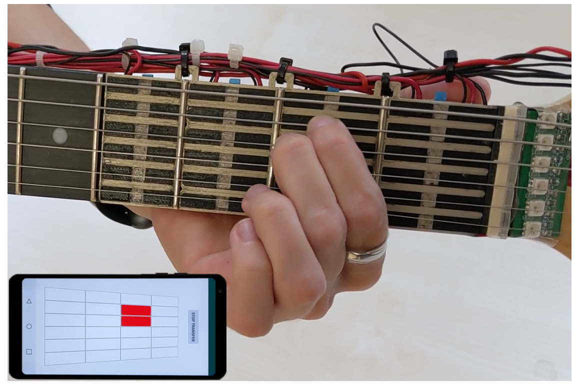
Based on 3D-printed touch sensors (cf. [33, 34]), we realized the requirement *finger feedback (fret)* as follows: As illustrated in Figure 3b, each fret is a 3D-printed structure that has six touch sensors printed in a conductive material. For our prototype, Proto-Pasta carbon-doped PLA. The printed sensors are embedded in and separated by an insulating material – for our prototype, we used regular PLA. Each fret is equipped with a touch controller chip that measures the capacitance at each of the six touch sensors. The measured capacitance is sent to the mobile app via Bluetooth for further analysis. The mobile app visualizes the touches (see Figure 3b and Figure 3c).

Using these touch sensors, we can capture three types of finger positions: First, in each fret, six finger positions that correspond to each string can be captured. Second, finger positions resulting from touching more than one sensor within one fret can be captured. That means that the student's finger is shifted vertically in the direction of another string. Finally, we can capture finger positions exactly between two frets on the separator resulting from a horizontal shift of the student's fingers. The second and third cases are important since those result in inaccurate playing. For instance, a student might touch a neighboring string, which mutes the string and impacts the played chord.

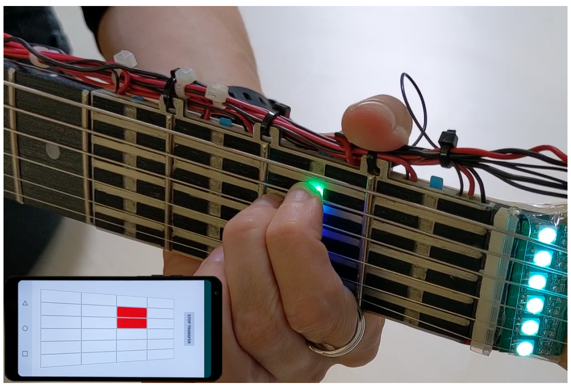
[1] www.github.com/Pinyto/lets-frets - last access 2021-01-05



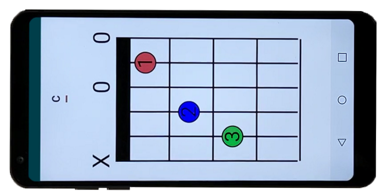
(a) LED: LEDs indicate which strings should be pressed.



(b) CS: The touched fret is captured by capacitive sensing and visualized.



(c) LED-CS: Combination of LEDs and capacitive sensing.



(d) Baseline: Smartphone showing fretboard charts.

Figure 3: The four conditions used in the study.

4.4 Adjustability

To realize the *adjustability* requirement, finger position capturing and visual guidance can be used separately or in combination. For instance, for practicing a new chord, students can use visual guidance first. Once they know how to place their fingers, they can choose a sequence of chords in the app. The app, as well as the guitar fretboard, displays the chords to the student and automatically switches to the next chords once the correct finger placement is recognized. After a while, students can switch off the LEDs completely and use finger position capturing only. The position capturing can furthermore be used to record playing sessions for analysis later on.

5 USER STUDY

This section presents a user-centered evaluation of *Let's Frets*. We evaluated the usability of the different feedback modalities of *Let's Frets* in comparison to a baseline when practicing new basic skills. We considered the practice of simple chords as a basic skill within our study. Our study design included four conditions that were evaluated in our study regarding effectiveness, efficiency, and user satisfaction. Three of them are modules of *Let's Frets* while fretboard charts served as a baseline (see also Figure 3):

(1) **Visual Indicators (LED):** The LEDs in the fretboard displayed target positions for the fingers. The targets were colored coded with one color for each finger. The LEDs on the nut of the guitar showed which strings the participant had to strum. The positions were also displayed in the smartphone app on a virtual fretboard chart.
(2) **Capacitive Sensing (CS):** In this condition, the finger position capturing was used. The current position of the fingers was depicted on a smartphone in front of the participant.
(3) **Visual Indicators and Capacitive Sensing (LED-CS):** A combination of conditions (1) and (2).
(4) **Fretboard Charts (Baseline):** The fretboard chart was depicted on a smartphone in identical dimensions like to sensing depiction in condition (2) and (3).

5.1 Apparatus and Study Task

The study utilized the aforementioned smart guitar *Let's Frets* with the accompanying feedback modalities. The participants were asked to sit on a chair such that they can place the guitar on their legs. The fretboard of the guitar was filmed without the participants' faces. A smartphone was placed in front of the participant.

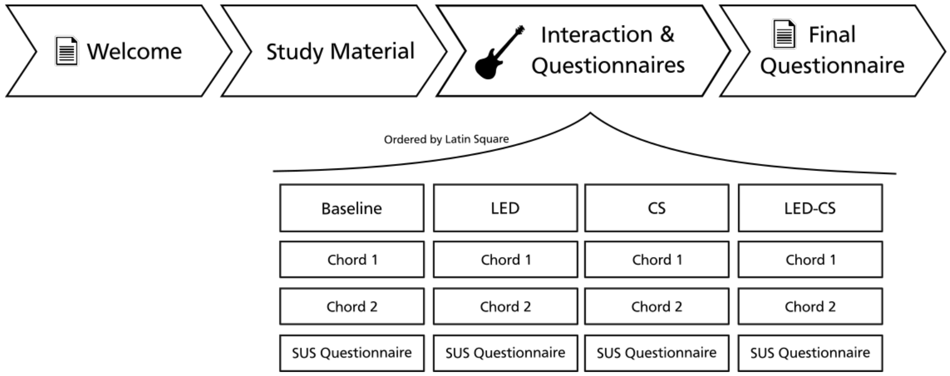


Figure 4: Procedure of our user study.

Considering the study task, we asked each participant to play eight chords during the study. We chose these guitar chords in an expert meeting with an experienced guitar teacher. The resulting chords are simple and have a similar complexity: C-Major, D-Major, E-Major, G-Major, A-Major, A-Minor, E-Minor, and F-Major7. In each condition, the participants were asked to play two chords. Over all participants, the order of chords was counterbalanced to avoid sequential effects. The participants were asked to play the chords by pressing and strumming the strings. We furthermore instructed them to notify the examiner once they thought to have fulfilled the task.

5.2 Study Design and Procedure

Our study was in a within-subject design, meaning that each participant interacted with all conditions. The order of conditions was given by a Latin square to avoid sequential effects. According to ISO 9241-11, usability is based on the criteria of effectiveness, efficiency, and satisfaction [37]. To determine effectiveness, we captured whether the participants were able to successfully play the guitar chords listed above (binary success). For efficiency, we considered the time (in seconds) until finger placement in the correct chord position. The time started with presenting the chord and ended with the notification from the participants. To capture both metrics, we used camera recordings. Finally, we employed the System Usability Scale (SUS) [4] to capture satisfaction. The procedure of our user study was as follows (see also Figure 4):

5.2.1 Welcome, Consent Form and Demographics. At first, we informed participants about the purpose of our study. We detailed the recordings that took place as well as the study's data protection policy, which aligns with the guidelines of the ethics committee at our institution. Next, we explained the consent form that each participant had to sign. Then, the participants provided demographics.

5.2.2 Study Material. We explained the study material to the participants, which consisted of one information sheet for each condition that explained the feedback module or fretboard charts in a standardized way. All information sheets were developed with a guitar teacher and one guitar professional and tested before the study.

5.2.3 Interaction and Questionnaires. The participants interacted with the conditions and fulfilled the tasks given by the examiner. After they reported completion, the examiner handled the SUS questionnaire. Having completed those, the examiner provided the next condition the participant had interacted with each of the four.

5.2.4 Final Questionnaire and Debriefing. The participant received a final questionnaire with open-ended questions that aimed to compare the different conditions. Finally, the participant was given the opportunity to ask questions. We did not reimburse the participants.

5.3 Participants

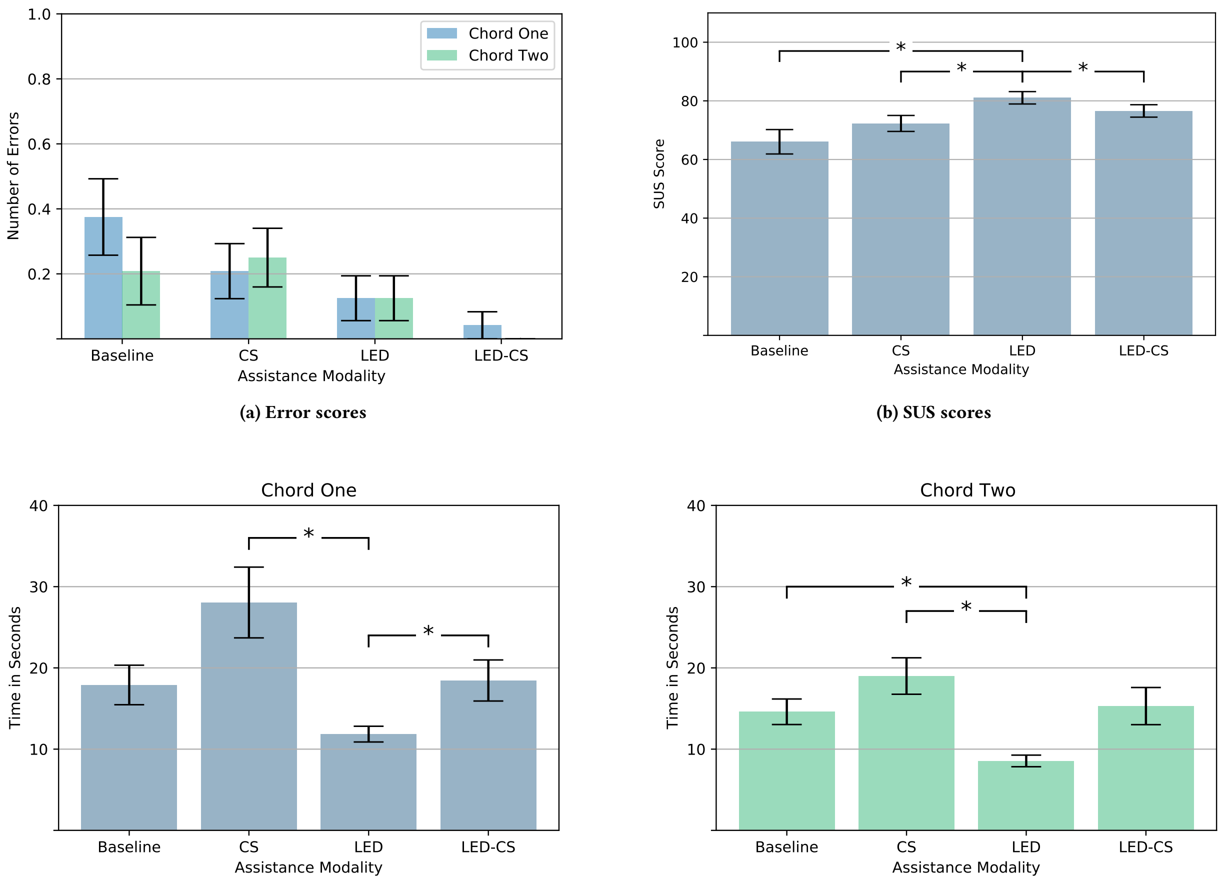
A total of 24 participants took part in our study. Participants were recruited via poster advertisements, mailing lists, and snowball sampling. The participants were between 20 and 39 years old (M = 26.83, SD = 5.36, 3 female, 19 male, one diverse). All participants did not play guitar before. However, about half of them stated to play another musical instrument. None of the participants played the guitar. Seven participants played piano, one played the flute, one played accordion, and one participant played the horn.

5.4 Results

In this section, we report the results of our evaluation. For reporting the results, we use the following abbreviations for the conditions: visual indicators are denoted as LED, capacitive sensing is denoted as CS. The combination thereof is denoted as LED-CS, and the fretboard charts are denoted as the baseline.

5.4.1 Effectiveness. As effectiveness, we considered whether a participant was able to play a chord correctly. For this, we used an error scoring system consisting of three error points: (1) the finger position on the fretboard is incorrect, (2) incorrect strings were strummed, and (3) the sound of the chord is incorrect. This results in a score between zero and three where the zero refers to a perfectly played chord. The scores were obtained through a post-hoc assessment of the recorded videos by two professional guitar players.

Fretboard charts resulted in 0.58 (SD = 1.08) errors, CS in 0.46 (SD = 0.86) errors, LEDs in 0.25 (SD = 0.68) errors, and LED-CS in 0.042 (SD = 0.20) errors accumulated over both sessions. We analyzed both chords separately for improvements regarding the playing efficiency. A repeated measures Friedman test found a significant main effect for the number of errors considering the first chord,



(a) Error scores

(b) SUS scores

(c) Task completion time chord one.

(d) Task completion time chord two.

Figure 5: User study results. Brackets indicate significant differences. The error bars depict the standard error.

$\chi^2(3) = 8.20$, $p = .04$. However, Bonferroni-corrected Wilcoxon-Signed rank tests did not find significant differences between the conditions. No significant main effect was found for the second chord. Figure 5a illustrates the number of errors for both chords.

5.4.2 Efficiency. We operationalized the playing time for efficiency. We measured the required time between the start and end of a playing session for each condition. The start was given by the presentation of the chord, and the end was given by the notification from the participants. We again considered both chords separately and investigated how the playing time varies between them.

A Shapiro-Wilk test indicated a non-normal distribution for all conditions in both chords ($p < .05$), hence we conducted a repeated-measures Friedman test for both chords and found a significant main effect for the first chord, $\chi^2(3) = 4.64$, $p = .005$, as well as for the second chord, $\chi^2(3) = 21.09$, $p < .001$.

Bonferroni-corrected (significance level set to p < 0.0083) Shapiro-Wilk tests show a significant effect between CS and LED feedback, $p < .001$, as well as LED and LED-CS, $p = 0.008$, when playing the first chord (see Figure 5c). Furthermore, a significant effect is observed between fretboard charts and LEDs, $p = .002$, as well as CS and LED feedback, $p < .001$, when playing the second chord (see Figure 5d).

5.4.3 Satisfaction. Satisfaction is given by the SUS score [4]. Fretboard charts received the lowest SUS score of on average 66.04 (SD = 20.40). According Bangor *et al.* [2] this refers to a "D" on the grade scale. Next is CS with an average of 72.29 (SD = 13.35) corresponding to a "C" on the grade scale. The LEDs received an average of 81.04 (SD = 10.35, "B" on grade scale) and the combination of modules (LED-CS) received a mean score of 76.56 (SD = 10.37, "C" on grade scale).

A Shapiro-Wilk test revealed a non-normal distribution of the data ($p < .05$). A repeated measures Friedman test shows a significant difference within the four conditions, $\chi^2(3) = 13.00$, $p = .005$. We conducted Wilcoxon signed-rank post hoc tests to find significant differences between pairs of the assistance modalities after applying a Bonferroni correction (significance level set to p < 0.0083). The post hoc test revealed significiant differences between fretboard chart and LEDs, $p = .002$, capacitive feedback and LEDs, $p = .004$, and LEDs and LED-CS, $p = .008$ (see Figure 5b).

5.4.4 Questionnaires. After all conditions, the participants received a final questionnaire in which we asked which condition they favor and why. Half of the participants favored the combination of both modules (LED-CS). Sample comments from these participants are:

- **P01:** *"This one had the best clarity and was easiest to use."*
- **P14:** *"I received very concrete feedback, that helped me better."*

16.6% of participants favored the CS condition because it is not required for them to look at the fretboard. Instead, they can look at the mobile device in front of them.

- **P12:** *"I like that I don't have to look at the fretboard."*
- **P15:** *"You can see if you pressed to many strings."*
- **P16:** *"Intuitive, easy to know what to do. I don't have to switch between different devices and screens."*

16.6% of participants favored the LEDs based on the provided guidance on the fretboard. They welcomed that the feedback is directly integrated into the fretboard:

- **P06:** *"It helped me most to get the instructions directly on the guitar, there was no need to look for the frets and strings."*
- **P16:** *"It is intuitive, I can quickly recognize what to do. No need to check the smartphone and the guitar."*

Other participants commented on the coloring of LEDs, which was perceived as counter-intuitive by two participants:

- **P04:** *"The assignment of fingers to color was not intuitive in the beginning because I had to remember it."*
- **P18:** *"The color assignment is difficult, I have to remember it."*

Finally, 8.3% of participants would favor traditional fretboard charts because those are more realistic for playing later on:

- **P01:** *"As an advanced player, I want to play directly from paper. This system helps me in learning the connecting between grips and names."*

Further feedback from the participants about the setups was related to the LED features:

- **P02:** *"I particularly liked that the LEDs showed which strings to strum."*
- **P17:** *"The glow from the LEDs is awesome."*

6 DISCUSSION

Our results show that guitar students can be effectively assisted during their practice by augmenting a guitar fretboard with additional visual support and finger position capturing using capacitive sensing. Further, our results show how different feedback modalities impact the practice of new guitar chords revealing that beginners are able to practice new chords faster using LED, while LED-CS elicits a low number of playing errors. In the following, we discuss these results in detail, and generalization possibilities of *Let's Frets* prototype into other musical instruments.

6.1 Assistance Needs to Adapt to Students

Learning to play the guitar is a long process that includes familiarization with an instrument, learning music notation, and sight-reading. The interviews and our user study revealed, that *Let's Frets* can facilitate guitar practicing for new guitar students. Further, *Let's Frets* can be adapted to support different skill levels. Familiarization with playing the guitar typically involves the full attention of students. In the beginning, this can be challenging because reading music notation and transposing it to the fretboard has not been acquired yet. To reduce the cognitive load of new students, visual guidance can be utilized. Participants in our study favored the combination module LED-CS and made the least errors when practicing new chords using it. LED-CS offers the most support, which is appropriate for beginners. Considering efficiency and satisfaction, the LED module was best, and participants also commented positively about it. The only negative aspects related to LEDs were that the colors for finger assignment were difficult to remember. Related work has investigated to long-term effects of LEDs, showing no long-term benefit delivered by LEDs compared to traditional notation [20]. Based on that and our studies, we conclude that LED modules should only be used in the very beginning until the student has learned to interpret traditional notations.

Besides practicing finger placements, *Let's Frets* could be leveraged for learning music notation. For example, the finger position capturing of *Let's Frets* can be combined with visual feedback in the supporting app that depicts the played note as fretboard chart, tab, or sheet music. This demands less visual attention to the guitar fretboard and affords students to pay more attention to the screen. Visualizing the played note in music notation in the app has the potential to enhance the student's orientation on the fretboard.

Once the music notations are well-known, the students can switch to the CS module that captures the position of their fingers on the fretboard. In doing so, students do not have to look at the fretboard and can compare their intention to the tracked position displayed on the app screen. Even skilled guitar players can use the finger position capturing to record their practice sessions or as support during composing. In particular, they could play newly composed material on the guitar, and the CS module automatically transforms it into tabs.

Within our study, we evaluated practicing simple chords. However, *Let's Frets* can be used for more advanced exercises. This includes practicing more complex chords, such as barre chords and chord progressions, but also sequences of tones like arpeggios, scales, or melodies.

6.2 Comparison to Other Systems

In this section, we discuss our results in comparison to related work and commercial systems. Several studies investigated visual guidance options for the guitar by integrating LEDs into the fretboard [20], projecting information on it by a projector [23, 24] or using head-mounted augmented reality displays [25]. Considering projection-based solutions, additional external components are required to realize the projection. Compared to *Let's Frets* additional components can have benefits and drawbacks. External projection components can be used as an add-on to an existing instrument. This is beneficial because instruments for learning purposes are not required. On the other hand, projection-based solutions require calibration and markers on the instrument. To realize visual guidance by Let's Frets, the fretboard requires modification. Consequently, the student either has to borrow a guitar with this functionality or purchase one. The commercial system FretZealot [10] offers an add-on system for upgrading guitars with removable LEDs.

In contrast to existing research that investigated integrated LEDs [20], *Let's Frets* offers the option to assign colors to each finger. Within the study, the participants valued that color support, but they needed some time to memorize the color assignment.

Besides supporting guitar learning, several research projects investigated other musical instruments like the violin [8, 28, 41], or the piano [12, 32, 42]. Our results confirm findings of related work that investigated augmented fingerboards of violins. More specifically, estimating the finger position on the fingerboard was perceived as beneficial [8, 28]. Considering the violin, the fingers have to be placed more accurately compared to the guitar because violins do not have frets.

6.3 Integrating *Let's Frets* into String and Key-based Instruments

The CS module that we integrated into the guitar fretboard can be integrated into other musical instruments to support their players. Finger placement on string instruments, like cellos or violins, is more crucial compared to guitars because these instruments do not have frets. Consequently, even a small misplacement largely impacts the played tone. Although the design of *Let's Frets* for fretless string instruments requires higher precision of finger capturing, capacitive sensing technology can deliver this accuracy by leveraging measurements of the capacitive resistance.

The idea of *Let's Frets* can be further extended to key-based instruments. Additional feedback and indication on the keys, such as on piano or an accordion, facilitates practicing finger placements and provides live feedback to students. From the technical perspective, similarly to our existing prototype of *Let's Frets*, the keys can be augmented with capacitive sensors and visual or tactile feedback. For instance, the keys could be 3D-printed of capacitive touch fields and insulating material. However, this might require additional empirical evaluation of our concept, given the limited generalizability of our results to other instruments.

6.4 Limitations and Future Work

In this section, we reflect on the limitations of our approach and motivate future work. As a first limitation, we consider the proof-of-concept realization of our prototype. We realized the *Let's Frets* modules for the first four frets. Based on the feedback of guitar teachers and professionals, we placed the wires that connect the fretboard to the on-board controller on top of the neck because this does not affect the task we evaluated in our study. However, such wire placement could affect specific playing styles, such as muting or pressing the deep E string with the thumb or the usage of capodastros. Furthermore, wires on top impact specific styles of tapping techniques. Based on that, future realizations of *Let's Frets* should integrate the wires into the guitar neck below the fretboard.

Most modules from *Let's Frets* are targeted to support practicing of skills with the hand that presses the strings. While the visual indicators can provide guidance for the other hand, e.g., with strings are to strum, the integrated sensors cannot capture the actions of the other hand. The strumming can be captured by piezo sensors [6, 35] or audio analysis [3, 26].

Based on our interview study, we proposed eight requirements for guitars that support practicing new skills. A third limitation is given because *Let's Frets* does not realize the requirements for finger feedback considering the applied force, strummed keys, and cost-effectiveness. Considering the later, the prototype of *Let's Frets* is based on a guitar assembly kit, and all components, including the printed fretboard, cost about 120$. However, future prototypes should consider the cost-effectiveness requirement. Furthermore, implementations of feedback for the applied force on the frets. As demonstrated by related work, the strumming feedback can be realized by piezo sensors [35]. Within this work, we investigated *Let's Frets* with participants that are new to playing the guitar. Future studies should extend this investigation by investigating participants with different skill levels.

Another stream of future work should investigate to make deliberate practice more connected to making music. For instance, participants in the interview study stated that backing tracks and drum-recordings could be used instead of a metronome to practice beat and playing accuracy. Such recordings, however, cannot automatically adapt to the player's current speed, and it is not possible to repeat sections without pausing and restarting the recording. Means to provide an automatic adjustment of backing tracks and recordings should be investigated in future work.

7 CONCLUSION

In this paper, we presented *Let's Frets* a guitar practice setup with different support modules. *Let's Frets* is based on requirements that we collected through in-depth interviews with guitar professionals and teachers. Our setup provides visual guidance by LEDs in the guitar fretboard. Furthermore, the fretboard can capture finger positions while playing and display them in an app. To evaluate the different feedback modules of *Let's Frets*, we conducted a user study with 24 participants that had no experience in guitar playing. In particular, we evaluated the feedback modules 1) visual guidance, 2) finger position capturing, 3) the combination thereof against fretboard charts as a baseline. Our results show that the participants favor the combination module, which also offered support regarding playing accuracy. Visual guidance delivered the quickest results and highest satisfaction scores. All modules performed better compared to fretboard charts, which are depictions of the fretboard. We conclude that our modular concept can support guitar players with different skill levels and discuss how *Let's Frets* can be leveraged for guitar practice and other activities, such as composing. Finally, we show how it can be integrated into other musical instruments and discuss opportunities for future work.

ACKNOWLEDGMENTS

This research work has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 326979514/3DIA). We furthermore would like to thank the people that participated in the interview and user studies. We furthermore thank Paul Seesemann who supported the data collection of the interview study, the guitar teachers Julian Gramm and Klaus Rosenthal for their feedback, and Rasmus Westphal for his performance in the video.

REFERENCES

[1] Jakob Abeßer. 2012. Automatic String Detection for Bass Guitar and Electric Guitar. In *Proceedings of the International Symposium on Computer Music Modeling and Retrieval (CMMR 2012)*. Springer, Cham, Switzerland, 333–352.

[2] Aaron Bangor, Philip Kortum, and James Miller. 2009. Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale. *Journal of Usability Studies* 4, 3 (2009), 114–123.

[3] Ana M. Barbancho, Anssi Klapuri, Lorenzo J. Tardon, and Isabel Barbancho. 2012. Automatic Transcription of Guitar Chords and Fingering From Audio. *IEEE Transactions on Audio, Speech, and Language Processing* 20, 3 (2012), 915–921. https://doi.org/10.1109/TASL.2011.2174227

[4] John Brooke. 1996. SUS - A Quick and Dirty Usability Scale. *Usability Evaluation in Industry* 189, 194 (1996), 4–7.

[5] Ozan Cakmakci, François Bérard, and Joëlle Coutaz. 2003. An Augmented Reality based Learning Assistant for Electric Bass Guitar. In *Proceedings of the 10th HCI International Conference on Human-Computer Interaction (HCI International 2003)*. CRC Press Taylor, Boca Raton, FL, USA, 1–2.

[6] Hongchan Choi, John Granzow, and Joel Sadler. 2012. The Deckle Project : A Sketch of Three Sensors. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*. University of Michigan, Ann Arbor, Michigan. https://doi.org/10.5281/zenodo.1178235

[7] Jacob Cohen. 1960. A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement* 20, 1 (1960), 37–46.

[8] David Dalmazzo and Rafael Ramirez. 2017. Air Violin: A Machine Learning Approach to Fingering Gesture Recognition. In *Proceedings of the 1st ACM SIGCHI International Workshop on Multimodal Interaction for Education (MIE 2017)*. ACM, New York, NY, USA, 63–66. https://doi.org/10.1145/3139513.3139526

[9] Shantanu Das, Seth Glickman, Fu Yen Hsiao, and Byunghwan Lee. 2017. Music Everywhere – Augmented Reality Piano Improvisation Learning System. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*. Aalborg University Copenhagen, Copenhagen, Denmark, 511–512. https://doi.org/10.5281/zenodo.1176350

[10] LLC. Edge Tech Labs. 2019. FretZealot. http://fretzealot.com/. [Online; accessed: 12-January-2021].

[11] Anders Ericsson, Ralf T. Krampe, and Clemens Tesch-Römer. 1993. The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychological Review* 100, 3 (1993), 363. https://doi.org/10.1037//0033-295X.100.3.363

[12] Tobias Grosshauser and Gerhard Tröster. 2013. Finger Position and Pressure Sensing Techniques for String and Keyboard Instruments. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*. Graduate School of Culture Technology, KAIST, Daejeon, Republic of Korea, 27–30. https://doi.org/10.5281/zenodo.1178538

[13] Eli Harrison. 2010. Challenges Facing Guitar Education. *Music Educators Journal* 97, 1 (2010), 50–55. https://doi.org/10.1177/0027432109334421

[14] Jacob Harrison, Alan Chamberlain, and Andrew P. McPherson. 2019. Accessible Instruments in the Wild: Engaging with a Community of Learning-Disabled Musicians. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '19)*. ACM, New York, NY, USA, Article LBW0247, 6 pages. https://doi.org/10.1145/3290607.3313037

[15] Kevin Huang, Thad Starner, Ellen Do, Gil Weinberg, Daniel Kohlsdorf, Claas Ahlrichs, and Ruediger Leibrandt. 2010. Mobile Music Touch: Mobile Tactile Stimulation for Passive Learning. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 791–800. https://doi.org/10.1145/1753326.1753443

[16] Incident. 2019. gTar. www.incidentgtar.com. [Online; accessed: 12-January-2021].

[17] Rocksmith International. 2019. Rocksmith. https://rocksmith.ubisoft.com/rocksmith/en-us/home/. [Online; accessed: 12-January-2021].

[18] Jakob Karolus, Annika Kilian, Thomas Kosch, Albrecht Schmidt, and Paweł W. Wozniak. 2020. Hit the Thumb Jack! Using Electromyography to Augment the Piano Keyboard. In *Proceedings of the ACM Designing Interactive Systems Conference (DIS '20)*. ACM, New York, NY, USA, 429–440. https://doi.org/10.1145/3357236.3395500

[19] Jakob Karolus, Hendrik Schuff, Thomas Kosch, Paweł W. Wozniak, and Albrecht Schmidt. 2018. EMGuitar: Assisting Guitar Playing with Electromyography. In *Proceedings of the Designing Interactive Systems Conference (DIS '18)*. ACM, New York, NY, USA, 651–655. https://doi.org/10.1145/3196709.3196803

[20] Joseph R. Keebler, Travis J. Wiltshire, Dustin C. Smith, and Stephen M. Fiore. 2013. Picking Up STEAM: Educational Implications for Teaching With an Augmented Reality Guitar Learning System. In *Proceedings of the International Conference on Virtual, Augmented and Mixed Reality (VAMR)*. Springer, Cham, Switzerland, 170–178. https://doi.org/10.1007/978-3-642-39420-1_19

[21] Chutisant Kerdvibulvech and Hideo Saito. 2007. Real-Time Guitar Chord Estimation by Stereo Cameras for Supporting Guitarists. In *Proceedings of the 10th International Workshop on Advanced Image Technology (IWAIT)*. 256–261.

[22] Ralf T. Krampe and Karl A. Ericsson. 1995. *Deliberate Practice and Elite Musical Performance*. Cambridge University Press, Cambridge, United Kingdom, 84–102. https://doi.org/10.1017/CBO9780511552366.005

[23] Markus Löchtefeld, Sven Gehring, Ralf Jung, and Antonio Krüger. 2011. guitAR: Supporting Guitar Learning Through Mobile Projection. In *Extended Abstracts of the CHI Human Factors in Computing Systems (CHI EA '11)*. ACM, New York, NY, USA, 1447–1452. https://doi.org/10.1145/1979742.1979789

[24] Markus Löchtefeld, Sven Gehring, Ralf Jung, and Antonio Krüger. 2011. Using Mobile Projection to Support Guitar Learning. In *Proceedings of the International Symposium on Smart Graphics*. Springer, Cham, Switzerland, 103–114. https://doi.org/10.1007/978-3-642-22571-0_9

[25] Karola Marky, Andreas Weiß, and Thomas Kosch. 2019. Supporting Musical Practice Sessions Through HMD-Based Augmented Reality. In *Mensch und Computer 2019-Workshopband*. Gesellschaft für Informatik e.V., Bonn, Germany, 1–5.

[26] Matthias Mauch and Simon Dixon. 2010. Simultaneous Estimation of Chords and Musical Context From Audio. *IEEE Transactions on Audio, Speech, and Language Processing* 18, 6 (2010), 1280–1289. https://doi.org/10.1109/TASL.2009.2032947

[27] Yoichi Motokawa and Hideo Saito. 2006. Support System for Guitar Playing Using Augmented Reality Display. In *Proceedings of the IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '06)*. IEEE Computer Society, Washington, DC, USA, 243–244. https://doi.org/10.1109/ISMAR.2006.297825

[28] Laurel S. Pardue, Christopher Harte, and Andrew P. McPherson. 2015. A low-cost real-time tracking system for violin. *Journal of New Music Research* 44, 4 (2015), 305–323.

[29] Linsey Raymaekers, Jo Vermeulen, Kris Luyten, and Karin Coninx. 2014. Game of Tones: Learning to Play Songs on a Piano Using Projected Instructions and Games. In *Proceedings of the 2014 CHI Human Factors in Computing Systems (Extended Abstracts)* (Toronto, Ontario, Canada) *(CHI EA '14)*. ACM, New York, NY, USA, 411–414. https://doi.org/10.1145/2559206.2574799

[30] A. B. M. (Boni) Rietveld. 2013. Dancers' and Musicians' Injuries. *Clinical Rheumatology* 32, 4 (01 Apr 2013), 425–434. https://doi.org/10.1007/s10067-013-2184-8

[31] Del Rio-Guerra, Marta Sylvia, Jorge Martin-Gutierrez, Vicente A Lopez-Chao, Rodolfo Flores Parra, and Mario A Ramirez Sosa. 2019. AR Graphic Representation of Musical Notes for Self-Learning on Guitar. *Applied Sciences* 9, 21 (2019), 4527.

[32] Katja Rogers, Amrei Röhlig, Matthias Weing, Jan Gugenheimer, Bastian Könings, Melina Klepsch, Florian Schaub, Enrico Rukzio, Tina Seufert, and Michael Weber. 2014. P.I.A.N.O.: Faster Piano Learning with Interactive Projection. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces (ITS '14)*. ACM, New York, NY, USA, 149–158. https://doi.org/10.1145/2669485.2669514

[33] Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A Series of Tubes: Adding Interactivity to 3D Prints Using Internal Pipes. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, New York, USA, 3–12. https://doi.org/10.1145/2642918.2647374

[34] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, New York, USA, 253–258. https://doi.org/10.1145/2807442.2807503

[35] Yejin Shin, Jemin Hwang, Jeonghyeok Park, and Soonuk Seol. 2018. Real-time Recognition of Guitar Performance Using Two Sensor Groups for Interactive Lesson. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '18)*. ACM, New York, NY, USA, 435–442. https://doi.org/10.1145/3173225.3173235

[36] John A. Sloboda, Jane W. Davidson, Michael J.A. Howe, and Derek G. Moore. 1996. The Role of Practice in the Development of Performing Musicians. *British Journal of Psychology* 87, 2 (1996), 287–309. https://doi.org/10.1111/j.2044-8295.1996.tb02591.x

[37] International Organization For Standardization. 1998. ISO 9241-11: Ergonomics of Human System Interaction – Part 11: Guidance on Usability.

[38] The Fretlight Guitar Store. 2019. FretLight. https://fretlight.com/. [Online; accessed: 12-January-2021].

[39] LLC. Synthesia. 2019. Synthesia – A Fun Way to Learn How to Play the Piano. https://www.synthesiagame.com/. [Online; accessed: 12-January-2021].

[40] Yoshinari Takegawa, Tsutomu Terada, and Masahiko Tsukamoto. 2012. A Piano Learning Support System Considering Rhythm. In *Proceedings of the International Computer Music Conference (ICMC)*. The International Computer Music Association, San Francisco, CA, USA, 325–332.

[41] Janet van der Linden, Erwin Schoonderwaldt, Jon Bird, and Rose Johnson. 2011. MusicJacket – Combining Motion Capture and Vibrotactile Feedback to Teach Violin Bowing. *IEEE Transactions on Instrumentation and Measurement* 60, 1 (Jan 2011), 104–113. https://doi.org/10.1109/TIM.2010.2065770

[42] Xiao Xiao and Hiroshi Ishii. 2010. MirrorFugue: Communicating Hand Gesture in Remote Piano Collaboration. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 13–20. https://doi.org/10.1145/1935701.1935705

[43] Qi Yang and Georg Essl. 2013. Visual Associations in Augmented Keyboard Performance. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*. Graduate School of Culture Technology, KAIST, Daejeon, Republic of Korea, 252–255. https://doi.org/10.5281/zenodo.1178694

[44] Kazuki Yazawa, Daichi Sakaue, Kohei Nagira, Katsutoshi Itoyama, and Hiroshi G. Okuno. 2013. Audio-Based Guitar Tablature Transcription Using Multipitch Analysis and Playability Constraints. In *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing*. IEEE, Piscataway, NJ, USA, 196–200.