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Perception of guitar strings on a flat visuo-haptic display^{*}

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Abstract. There is a rapid growth of interest in digital musical instruments due to advantages they present over their physical counterparts such as portability and novel experiences. However, these instruments still rarely provide haptic feedback, which results in weakened user experience. This study investigates whether haptic renderings of three guitar strings are discriminated by touch and whether they provide a realistic sensation of plucking a guitar string. Specifically, five methods to record and replay the vibrations induced by the plucking of a guitar string were tested. Three procedures relied on recordings made on the right hand’s index finger, which underwent three types of filtering. Another one was recorded on the left hand kept motionless on the guitar’s fingerboard. The fifth method recorded the vibrations directly on the neck of the guitar. The results revealed that good discrimination of the rendered string occurred only for recordings made on the motionless left hand’s index finger or on the guitar. Participants also rated these conditions as being the most realistic, regardless of whether they were acquainted with musical instruments. Overall, this study shows that distinct guitar strings can be rendered by vibrotactile feedback and that tactile noise due to the interaction impairs their recognition and perceived realism.

Keywords: Vibrotactile rendering · Guitar string discrimination · Visuo-haptic perception.

1 Introduction

The field of musical instruments becomes increasingly digitalized, creating a category of instruments called digital musical instruments (DMI). This new category of instruments brings several advantages in comparison to their physical counterparts by overcoming the physical limitations imposed on tangible instruments [17]. However, despite these advantages [16, 6], DMIs currently suffer from a large drawback compared to real instruments, which is the absence of haptic feedback. When a musician plays an instrument, a loop is created in the sense

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of touch. The musician gives energy and perceives the instrument’s response, creating a rich haptic exchange. The absence of compelling haptic feedback does not allow for this loop to be obtained in an optimal manner, thus diminishing the musician’s ability to control the device and express itself. In addition, the performance and fidelity of the notes are reduced, and the listeners are also impacted by a less expressive performance [14]. Indeed, the sense of touch is an essential sense for interacting with world around us. It enables us to explore the surrounding environment [10] and exhibits an astonishing sensitivity to subtle vibrations up to 1000 Hz [3] as well as small transient changes in the contact forces [7].

Various studies have already investigated the impact of adding a haptic feedback on musical instruments [11, 20, 1, 15] and conclude that such feedback can be helpful for musical perception. The addition of a haptic feedback is useful to improve the quality of play of the musician, but also, it increases the ease of learning, and the pleasure of practicing. Moreover, it facilitates access to people suffering from visual, auditory or deaf blindness impairments [19, 18, 12]. In order to feel these digital instruments, it is necessary to be able to perceive their textures and vibrations and numerous studies have shown that it is possible to discriminate textures, edges, shapes or vibrations that are generated by haptic devices [2, 5, 8]. Moreover, coupling haptic feedback with visual representation improves perceptual capacity [9, 13], representation in memory [4], and spatio-temporal accuracy [1]. This study aims to investigate how different types of haptic rendering of a guitar string, which are coupled with an accurate visual rendering, are discriminated and perceived by users. Specifically, we investigate the capacity of users to recognize each digital string and their rating of the achieved realism in five experimental conditions.

2 Materials and methods

2.1 Data Collection

To be able to compare different methods for haptic rendering of guitar string’s vibrations, we measured the vibrations elicited by the string on different locations:

- The tip of the right hand’s index finger: The measure is performed while this hand plucks the string (Fig.1.A).
- The tip of the left hand’s index finger: This finger pushes on the string at the level of the guitar’s fingerboard and stays motionless during the recording (Fig.1.B).
- The guitar fingerboard: The measure was performed with the accelerometer placed directly on the wood of the guitar’s neck (Fig.1.C).

These measuring locations aimed to test whether signal components generated during the movement or during the interaction between the sensor and the nail impact the discrimination capacity of the user and the sensation of realism. The

guitar was held in a natural way; the right hand plucks the string, the left hand holds the neck and pushes on the string. The measures were performed with a PCB352A21 accelerometer that has a sensitivity of 10 mV/g, a measure range of ± 500 g pk, and a frequency range between 1.0 and 10000 Hz. The data were collected with a sampling frequency of 6250 Hz. For each position, three different notes were recorded corresponding to the vibration of three open strings : High (note E_4) at 329 Hz, Medium (note G_3) at 196 Hz and Low (note A_2) at 110 Hz. These three open strings were found sufficiently spaced in frequency to enable recognition significantly above chance but still challenging enough to prevent perfect performance.



Fig. 1. Measurement of the string’s vibration with an accelerometer placed at several locations. A) On the right hand’s index finger. B) On the left hand’s index finger. C) On the guitar fingerboard

2.2 Spectral analysis

After collecting the data, the frequency spectrum of each recording was characterized through a fast Fourier transform. The frequency spectra recorded on the right hand (Fig.2.A) and on the left hand (Fig.2.B) differ mostly by the presence of low frequency distortion related to the plucking of the strings by the right hand. In the case of measurements performed directly on the guitar fingerboard (Fig.2.C), the transmitted frequencies are less attenuated than in the other two cases where they are filtered by the skin.

Out of the recordings on the right hand’s index finger, we generated three haptic signals: the original signal (Right hand), a low-pass filtered version at 70 Hz (Right hand < 70 Hz), a high-pass filtered version at 70 Hz (Right hand > 70 Hz). We implemented these frequency filters to preferentially activate the tactile channels respectively related to FA1 (<70 Hz) and FA2 (>70 Hz) tactile afferents with the aim to investigate whether filtering low-frequency tactile noise or the high-frequency peaks would impact perception.

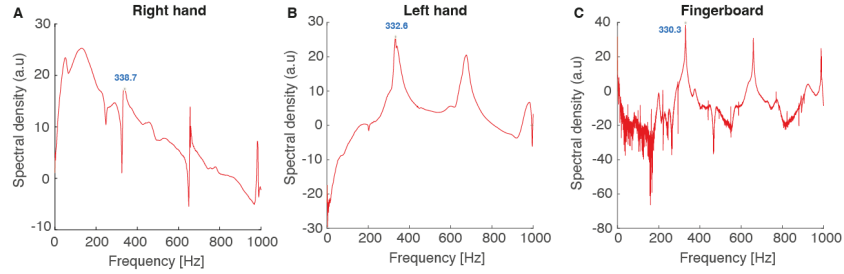


Fig. 2. Fast Fourier transform of the guitar string vibration signals, which are measured with the accelerometer. A) Right hand’s signal. B) Left hand’s signal. C) Guitar fingerboard’s signal.

2.3 Visual interface

In addition to the haptic feedback, a visual feedback of the strings’ vibration was implemented on Java Processing (Fig.3) following the equation of a vibrating string fixed at both ends, which was analytically computed:

$$y(x, t) = \sum_{p=1}^N A(p) \sin\left(\frac{p\pi}{L}x\right) \cos(\omega_p t) e^{-0.1\omega_p t} \quad (1)$$

With :

$$\omega_p = \frac{p\pi}{L} \sqrt{\frac{T}{\mu}} \quad (2)$$

$$A(p) = \frac{2a}{p^2\pi^2} \frac{1}{\alpha(1-\alpha)} \sin(p\pi\alpha) \quad (3)$$

For each note, Equation 1 was implemented in real time, except for a slight delay generated by the software ($\simeq 2$ ms). A represents the amplitude of the string in relation to the y-axis (width of the screen), α represents the ratio of the location where the string is plucked in comparison to the total length. Several mechanical parameters related to the string are also considered. L represents the total length of the string, T is the string tension, ω_p is the angular frequency, which coincides with the harmonic frequency (f_p), and μ represents its linear mass. There are also some parameters specific to the simulation such as the sampling frequency, the harmonic number p , and the total number of harmonics N . We computed only the fundamental frequency for the visual rendering because we were limited by the refresh rate of the visual display ($p=1$, $N=1$, High=329 Hz, Medium=196 Hz and Low=110 Hz).

2.4 Perception study

To conduct the perception study, a vibrotactile actuator MM3C (Tactile Labs, Canada) was used. This actuator is specially designed to cover the frequency

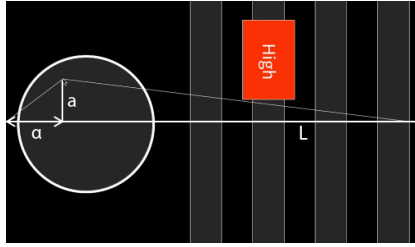


Fig. 3. Representation of a guitar string on the visuo-haptic display.

range perceived by the human finger. However, it distorts the signal at very low frequencies (< 30 Hz). In order to minimize disturbance during the test, a high-pass finite impulse response filter (FIR) at 30 Hz was used on each sample. No other distortion was observed during reproduction of the signals hence we did not apply additional low-pass filtering. In addition to the actuator, a 7-inch touch screen was used with a display frequency of 47 Hz. It enabled the participants to physically pluck the string, thus adding realism to the action.

Participants had to recognize three types of notes: high (E_4), medium (G_3) and low (A_2). For each of the five types of feedback, a total of 30 samples had to be recognized (10 per note type). The users place the index finger of their non-dominant hand on the actuator, which is located at the top of the screen (Fig.4). Then, they pluck the string on the tablet with their dominant hand, as if they were playing on a real guitar (Fig.4). After releasing the string, visual and haptic feedbacks are played simultaneously. Finally, after a few seconds, another screen appears that asks the participants which note was played: high, medium, or low. They choose one of them by pressing the corresponding button. The order of the blocks and of the notes within them are pseudo-randomized. In addition to recognizing the notes, participants are asked to rate the realism of the feedback they had just played in comparison with the impression of playing with a physical guitar. The score is reported using a scroll bar between 0 and 100%. Before each experimental block, which relates to a specific feedback type, participants familiarize themselves with the feedback by playing each note twice with knowledge of its type.

This study took place in an isolated space and participants wore ear muffs and earplugs in order to prevent auditory feedback. The study lasted between 25 and 30 minutes. In total, 21 people participated, 7 women and 14 men (mean age = 31.2, SD = 11.8). Participants also answered a questionnaire about their musical knowledge and experience with guitar playing. They rated their level of musical knowledge on a Likert-scale from 1 to 7 and they additionally reported whether it relates to guitar. 11 participants self-reported as guitarists among the 21 of the study. This question aimed to probe whether their musical knowledge influences their answers to the task. This study was conducted in accordance

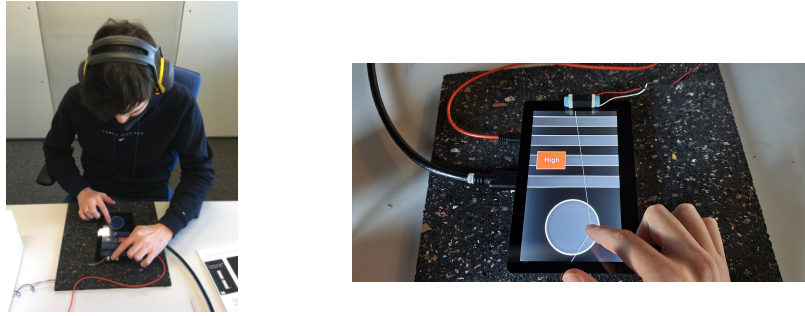


Fig. 4. The experimental set-up and the user's interaction with the simulated string

with the principles of the declaration of Helsinki and all participants gave their informed consent.

3 Results

To investigate the impact of the feedback type on recognition of the played note and the sensation of realism, we performed one-way ANOVA statistical analyses after verification of the data by a d'Agostino-Pearson normality test. The ANOVA analysis related to recognition of high, medium, and low notes between the five feedbacks (Fig.5.A) showed a significant effect of the haptic feedback type on the capacity of discrimination ($F = 8.713$, $p = 0.0002$). A post-hoc Tukey's multiple comparisons test was performed between individual feedbacks. Five post-hoc comparisons were found significant with $p < 0.05$: right hand vs. fingerboard, right hand < 70 Hz vs. left hand, right hand < 70 Hz vs. fingerboard, right hand > 70 Hz vs. left hand, and right hand > 70 Hz vs. fingerboard. Overall, significant comparisons occurred only between the feedbacks related to the right hand's recordings and those related to the left hand or fingerboard recordings. Another ANOVA was performed on the ratings about the feedback realism (Fig.5.B). The results from the analyses showed a significant effect of the feedback type on the quality of the rating ($F=7.444$, $p = 0.0002$). Five post-hoc comparisons were also found significant with $p < 0.05$: right hand vs. left hand, right hand vs. fingerboard, right hand < 70 Hz vs. fingerboard, right hand > 70 Hz vs. left hand, and right hand > 70 Hz vs. fingerboard. Overall, the significant differences observed for the recognition task were similar to those observed for rating the realism.

Generally, it appears that haptic feedback generated from recordings on the right hand, which is plucking the string, are less recognized and appreciated compared to the other feedback types.

The statistical test did not show significant differences between the experimental conditions related to the right hand either for note recognition or realism rating. Thus, filtering the signal recorded on the hand that plucks the guitar did not impact perception. The confusion matrices of the three main feedbacks were

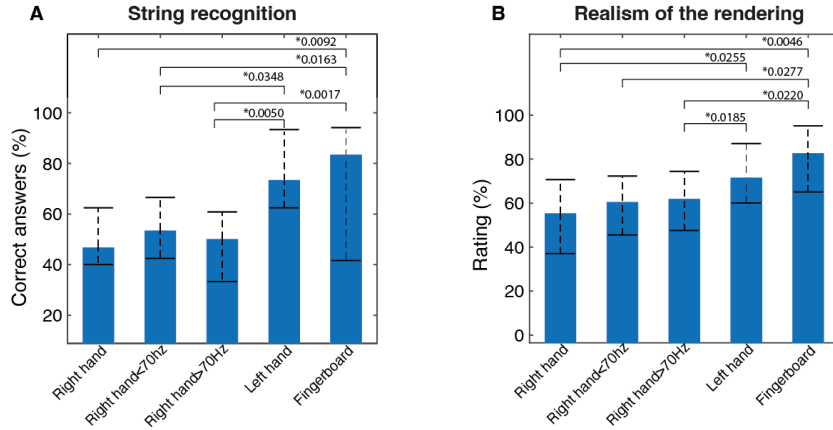


Fig. 5. A) Percentage of correct answers at the recognition task. The blue bars represent the median across participants and the error bars represent the lower and upper quartiles. B) Same plot for the rating of realism.

also computed showing similar trends. The confusion matrix when the feedback stems from recordings on the right hand (Fig.6.A) has a success rate of about 50%, unlike the other two matrices that have success rates over 70% (Fig.6.B & C). They also show that confusion mainly occurs between the high and medium notes, whose recognition is worse than for the low note regardless of the feedback type.

A Right hand				B Left hand				C Fingerboard			
	High	Med	Low		High	Med	Low		High	Med	Low
High	50	31.43	10	High	74.29	29.52	8.10	High	67.62	35.24	0.95
Med	32.86	53.33	33.33	Med	18.57	62.86	8.10	Med	27.62	60.95	9.52
Low	17.14	15.24	56.67	Low	7.14	7.62	83.81	Low	4.76	3.81	89.52

Fig. 6. Confusion matrix of the users' correct answers for the different feedback types. A) The right hand's feedback without filtering. B) The left hand's feedback. C) The guitar fingerboard's feedback

4 Discussion

The results of our study show that haptic feedback that stem from recordings on the hand that is plucking the string is significantly less recognized and appreciated than when the feedback is recorded on the the immobile left hand's index finger or on the guitar itself. Thus, the tactile noise generated by the kinesthetic interaction has a real impact on discrimination capacity, strongly reducing it. Moreover, users rate higher the realism when the recording is not impacted by

kinesthetic motion (see Fig.7). However, even when tactile noise distorts the signal and the signal is further filtered, performance is around 50% hence superior to chance level. This means that the users keep a certain capacity to discriminate visuo-haptic string rendering even if the recording is noisy or part of the frequency spectrum is missing due to filtering.

Interestingly, the string vibration recorded directly on the guitar’s neck hence without the finger in the recording loop was the highest rated by almost everyone. The absence of perturbation by the guitar plucking movement and of resonance damping by the fingertip have probably played a role in this condition being felt the most compelling.

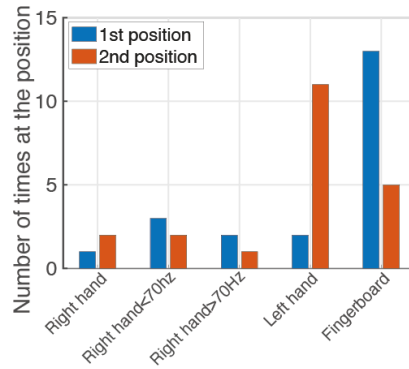


Fig. 7. User preferences. In blue, the feedbacks that obtained the highest ratings by the users during the experiment. In orange, those whose rating was the 2nd highest.

We can make a slight reservation concerning the similarities in the discrimination and rating abilities of the users between the three conditions that were designed by filtering the measurements on the right hand. The objective of the filtering differentiating the three feedbacks was to target the activation frequencies of the tactile channels related to FA1 and FA2 tactile afferents, respectively. However, the resulting signals still encompassed tactile noise around the cut-off frequency, which blurred the differences between the three conditions that used the recording from the right hand.

However, this does not affect the conclusion that the feedbacks, in which tactile noise due to kinesthetic interaction is present, are significantly less recognized and are rated as less realistic. In spite of the fact that presentation of the experimental blocks (i.e. feedback types) and the order of the trials were randomized between participants, we still noticed a learning phenomenon during the experiment (Fig.8). The recognition performance continuously improves with the progression of the blocks (Pearson’s Correlation, $p = 0.0193$). This progression may be due at first to the discovery of the experiment, which might have required some time to master. However, it is astonishing that performance at recognizing the notes continued to improve after the first blocks had passed.

We also asked participants to rate their musical knowledge and whether it relates to guitar. However, we found no indication that musical experience or experience with guitar playing influenced their perception of the rendered guitar strings.

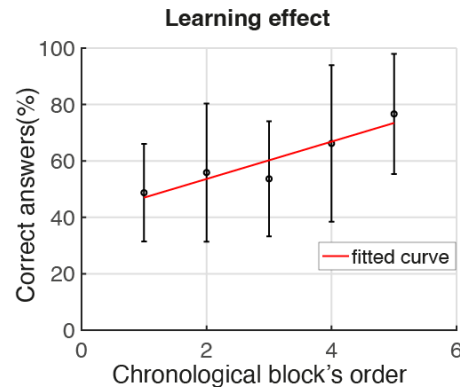


Fig. 8. A linear fit is performed on the average of individual performances across the experimental blocks in chronological order (Mean \pm SD).

5 Conclusion

Our study shows that recognition of a digital guitar string varies greatly depending on how the signal is recorded. Users perform better with feedback without the tactile components related to string plucking, thus when sensing solely the instrument's response. Furthermore, the realism of string vibrations recorded on the motionless finger or directly on the guitar is consistently rated higher by participants with a further preference for the direct recording on the guitar.

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