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A Longitudinal Study of Haptic Pitch Correction Guidance for String Instrument Players

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***Abstract*— This paper reports a six-day longitudinal study of haptic pitch correction guidance conducted with 18 novice string instruments players. The study compared a standard chromatic tuner and a haptic tuner (HapTune), which deliver information through the visual and the haptic (tactile) channel, respectively. Experimental results showed that HapTune was as effective as the chromatic tuner in improving the participants' skills for playing correct pitches. Further, HapTune seemed to cause less visual distraction to the participants' visual attention to score reading during string instrument play. These results suggest good viability of HapTune as an alternative of chromatic tuners, especially for visually-impaired users.**

Fig. 1. Examples of chromatic tuners: gStrings on Android (left) and Korg CA-30 (right).

I. Introduction

String instruments such as violin and viola are regarded difficult to learn. Playing a string instrument requires a variety of sub-skills, such as posturing and bowing, as well as simultaneous music score reading. Mastery of even sub-skills is not easy and takes years of practice; for example, a player needs at least 700 hours of practice to become proficient in only basic bowing [1]. Several devices have been used to help novice players, including bow guides for bowing training and metronomes for the guidance of accurate tempos.

Playing correct pitches is an essential but challenging skill to learn for a string instrument. The pitch produced is largely determined by the fingering position on the string, but most string instruments do not have physical guides (like frets in a guitar) for that. The majority of novice players cannot distinguish misplayed pitches, which can be off by only a few hertz from the desired pitches. As such, the learner practices playing correct pitches after learning basic bowing and posturing.

Chromatic tuners have been widely used as an aid for pitch correction. They are effective in delivering pitch errors visually using a gauge and text (Figure 1). However, chromatic tuners require the player's visual attention, and this often hinder accurate reading of music scores. Most chromatic tuners also have a small display, which makes the player move his/her neck or even torso to see the screen. This is apt to disturb the player's posture that needs to be maintained. Several VR- and AR-based learning aids have been developed for string instruments [2], [3], [4]. However, they focus on basic bowing and posturing, not correct pitch playing, and still require the player's visual attention.

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Haptic feedback can be an alternative. The haptic channel is less involved in sensory feedback during practice of string instruments, and it is effective in communicating relatively simple information as to movements. Such examples for musical instrument learning include a tactile jacket that provides vibrotactile guidance to teach violin bowing and posture [5], [6] and a commercial exoskeleton (Concert Hands) that imparts both force and vibrotactile feedback to help correct fingering in playing the piano [7]. The rhythm of drum playing can be guided using haptic stimuli [8], [9], [10]. For pitch correction, only few haptic aids have been studied [11], [12], including our prior work about HapTune (haptic tuner) [13].

Our previous paper in [13] introduced HapTune as a learning aid of string instruments for pitch correction. HapTune provides vibrotactile feedback to correct the played pitch using two vibrotactile actuators stimulating the players' left upper and lower arm. The sign of pitch error is represented by the stimulation site using a metaphor of height, and the absolute magnitude of pitch error is indicated by the strength and rhythm of stimulation using redundant information coding. A user experiment showed that the overall identification performance was over 95% with merely 65 errors out of 1400 trials, and only two misses were caused by misperceiving the stimulation location (the sign of pitch error).

In this paper, we present a longitudinal study carried out to evaluate the long-term performance of HapTune. A six-day between-subjects experiment was conducted with 18 novice string instrument players in order to compare the effectiveness of HapTune for pitch correction to that of a chromatic tuner. We also looked at the ability of the two tuners for preventing the occurrences of unintended negative effects such as visual distraction and bad posture. Experimental results demonstrated the viability of HapTune as an aid for pitch correction and also revealed its relative advantages and disadvantages.

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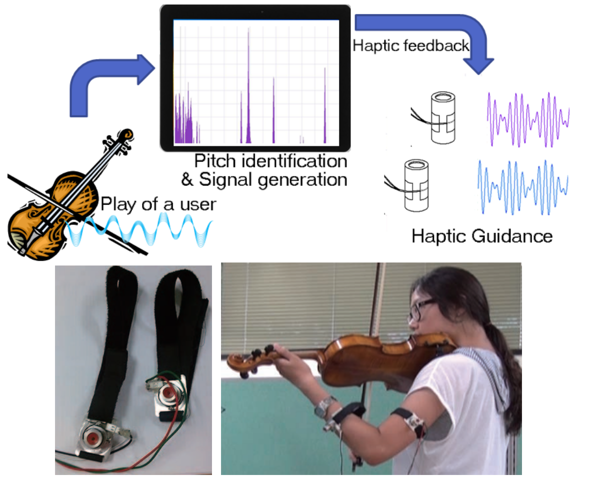

Fig. 2. Overview of HapTune (top). Vibration actuators (TactileLabs, Haptuator) attached to arm bands (bottom left) and a violin player wearing the two arm bands (bottom right).

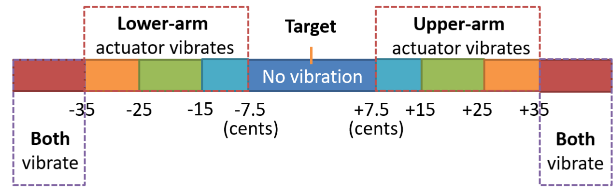

Fig. 3. Haptic feedback design of HapTune.

TABLE I
DESIGN OF VIBROTACTILE STIMULI.

Region (Error)	Waveform	Inter-pulse gap	Amplitude	Pulse width
7.5 – 15		100 ms	< 2 G (weak)	20 ms
15 – 25		60 ms	3–3.5 G (medium)	20 ms
25 – 35		20 ms	4.5–5 G (strong)	20 ms
35 – 50		<5 ms	4.5–5 G (strong)	60 ms

II. The HapTune System

A. Overview

HapTune [13] captures the sound produced by a string instrument using a microphone and analyzes the sound using real-time signal processing algorithms to identify the current sound pitch. This is done by computing the spectrum of the sound using fast Fourier transform (FFT) and extracting peak(s) from the spectrum. Then the target pitch is determined as the nearest pitch in the equal tempered scale based on the concert pitch (A4=440 Hz) from the current pitch. Then, the error between the played and the target pitch is calculated in *cents*[1]. This is the same computational procedure used in chromatic tuners.

In the present study, we used the same apparatus and software used in our previous study [13]. An overview of the system is shown in Figure 2. An Android application on a tablet PC (Samsung, Galaxy Tab 10.1) was made for software implementation of HapTune and a chromatic tuner.

HapTune notifies the pitch error to the user by providing vibrotactile feedback through two actuators worn around the left upper and lower arms of the user using armbands. We chose the two arm locations since they move less while playing a string instrument. Also considering that a string player adjusts the pitch by moving the left fingers, it is more direct and effective to give vibrotactile feedback to the left arm. Each of the two armbands includes a vibrotactile actuator (TactileLabs, Haptuator) connected to a custom amplifier. As stimuli, we use vibrotactile pulses made by superimposing 80 and 100 Hz sinusoidal signals. The subjective impression of superimposed vibrations is generally rougher than individual sinusoidal vibrations [14], so more suitable for warnings.

[1] *Cent* is a logarithmic unit of measure used for musical intervals. In the equal tempered scale, 100 cents correspond to a semitone. The ratio between two frequencies one cent apart is $2^{\frac{1}{1200}}$ (≈ 1.00057779). The pitch error in cents is calculated by

$$e_{cent} = 1200 \times log_2 \frac{f_p}{f_d}$$

where f_p is the frequency of a played pitch and f_d is the target pitch. For example, a user plays A4 (440 Hz) with 445 Hz, the error is 19.56 cents.

B. Vibrotactile Feedback Design

HapTune provides information about pitch errors to the user as the same way to our initial study [13]. The sign of pitch error is represented using a metaphor of height: vibrations produced by the upper (lower) armband indicate that the played pitch is higher (lower) than the target pitch. To transmit the absolute value of pitch error with high recognition performance, we rely on a redundant information coding scheme. We co-vary the multiple stimulus dimensions of amplitude, pulse width, and inter-pulse gap to control the perceptual intensity and rhythm of a vibration. Specifically, the continuous pitch error is mapped to eight different vibrotactile stimuli (including no vibration), as depicted in Figure 3 and Table I. While chromatic tuners display pitch errors in a continuous scale, our discrete-scale design take into account the limited performance of human tactile perception [15]. Our design also reflects the fact that the acceptable level of pitch error is about 10 cents even for experts [16].

For the magnitude coding, the absolute value of pitch error is partitioned to five intervals: 0–7.5 cents (correct pitch), 7.5–15 cents, 15–25 cents, 25–35 cents, and 35–50 cents, as shown in Figure 3. Then the corresponding vibration is triggered using the parameters shown in Table I with the designated actuator(s). If the absolute pitch error is between 35 and 50 cents (red regions in Figure 3; near the border between two adjacent semitones), both actuators are turned on to give an intense warning the greatest-level absolute pitch error. This is done regardless of the sign of pitch error to handle discrete changes in subsequent target pitches in the equal tempered scale; if the absolute pitch error is larger than 50 cents, the target pitch is changed to the subsequent semitone. For example, suppose that the current target pitch

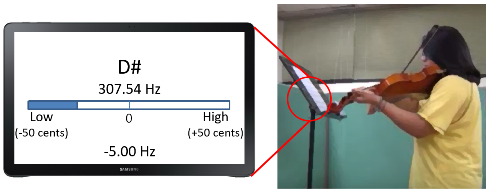

Fig. 4. Chromatic tuner used by the visual group. It presents the name of the current pitch, the frequency played, and the pitch error and its visualization.

is C with a pitch error of 49 cents. If the pitch error from C is increased to 51 cents, the target pitch is changed to the next semitone, C$^{\#}$, and the pitch error becomes -49 cents. This discontinuity is inevitable without knowing the users' true intended pitch and is also common with chromatic tuners.

III. Methods

We conducted a six-day experiment to evaluate the effectiveness of HapTune for pitch correction while preventing visual distraction. Use of chromatic tuners was also tested as reference.

A. Participants

Eighteen novice string players (13 males and 5 females; 17 to 25 years old with an average of 19.89 years; 3 to 30 months of experience with an average of 15.4 months) participated in this user study. All participants played strings as a hobby, and 14 of them had had lessons by professionals. The participants were paid for their participation.

B. Experimental Conditions

Participants were divided into two groups (visual and haptic), nine each, in a between-subjects design. The group was balanced in terms of the period of learning. The average periods of learning were 15.3 and 15.4 months, respectively.

During practice, the visual group was provided with visual feedback using a chromatic tuner (Figure 4). The feedback consisted of the syllable name of target pitch (e.g., C, D$^{\#}$), the current pitch (frequency), and the pitch error written in text and also visualized using a horizontal bar gauge. The haptic group was assisted with haptic feedback from HapTune, as described in Section II-B.

C. Experimental Procedure

As shown in Figure 5, participants completed the experiment on six consecutive days. On day 1, participants were invited to our laboratory and given instructions as to the experimental procedure. Then they played an étude score (Figure 6) with the string instrument (violin or viola) they had been learning without the chromatic tuner or the HapTune, i.e., without feedback. This pretest was to measure the baseline performance of participants prior to practice.

On day 2 to day 6, participants had daily practice sessions in which they were always assisted with the feedback method (visual or haptic) assigned to them. Each session had the same structure. Participants played the entire étude score at the beginning of the session, then practiced any parts of the score as they wanted in the rest of the session (20 minutes

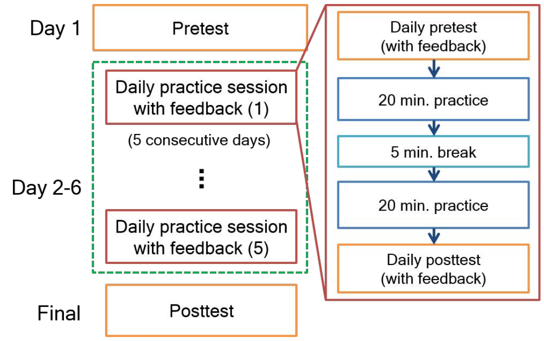

Fig. 5. Experimental procedure of the user study.

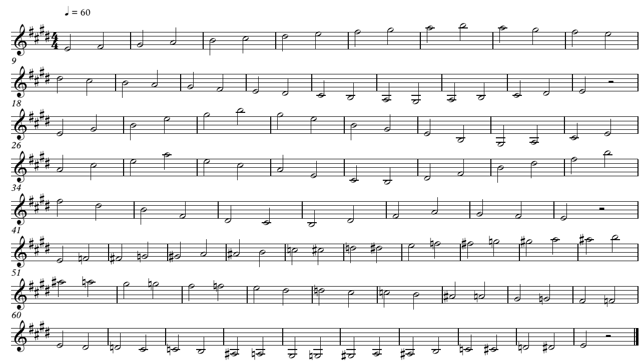

Fig. 6. The musical score used in the experiment. It concatenates scale études No. 49, 115-(a), and 117-(a) in [17].

of practice, 5 minutes of break, and then 20 minutes of practice), and played the entire étude score again at the end of the session. The daily pretest and posttest were for both practice and confirmation of the learning taking place.

On the last day, right after the last practice session, participants played the entire étude score once again without feedback. This posttest was to assess their final performance improvement over the five-day practice.

All the practice and test sessions were recorded using a digital video camera for data analysis.

D. Data Analysis

From the recorded videos, we obtained four performance measures. The videos for the pretest and posttest (carried out without feedback) were used to evaluate the effectiveness of practice. Those for the daily pretests and posttests (with feedback) were used to form the learning curves.

Two measures accounted for the participants' performance improvement. The first measure was the absolute pitch error (APE). An APE was calculated for each note in the étude score by taking the frequency difference in cents between the pitch played by a participant and the target pitch. The second measure was the number of misplayed pitches (NMP). When the error between played and target pitches exceeded 50 cents (half semitone), the played pitch was considered misplayed.

The other two measures are related to the negative effects of pitch correction aids. One is the number of pauses (NP) made during a play, and the other is the number of bad postures (NBP; extreme movements or bending their torso or

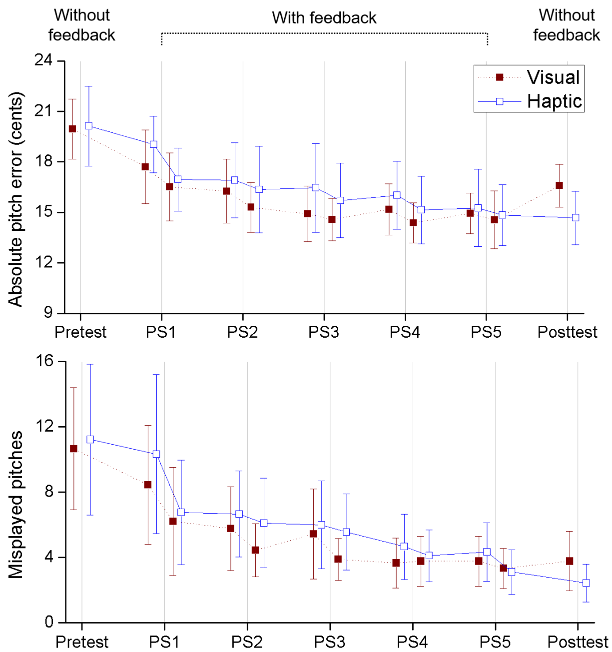

Fig. 7. Performance measured in the user study: the mean absolute pitch error (top) and the mean number of misplayed pitches (bottom). PS1–5: practice session 1 (day 2) to 5 (day 6). Each practice session gives two numbers for the daily pretest (left point) and posttest (right point). Error bars show 95% confidence intervals (CIs).

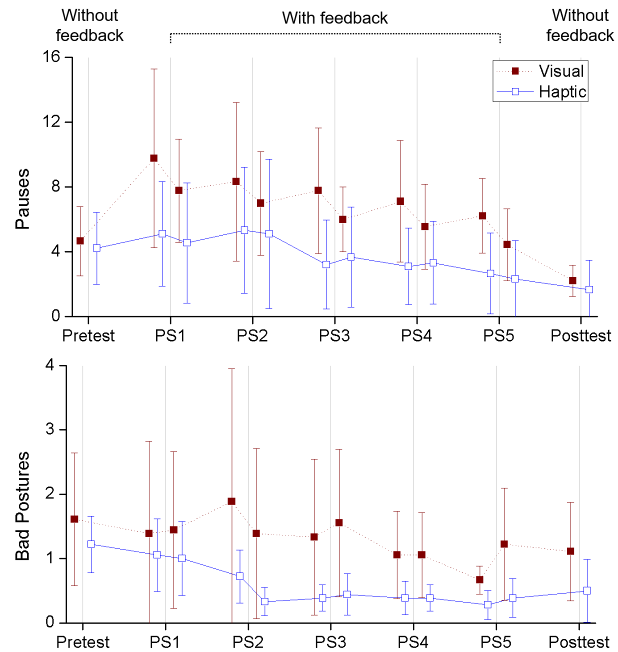

Fig. 8. Performance measures for negative effects: the mean number of pauses (top) and the mean number of bad postures (bottom).

neck forward). The former occurs for a number of reasons, but misreading the score, e.g., to read a chromatic tuner's screen, is primary. The latter is mostly due to visual attention to the small screen of a chromatic tuner. We hoped to understand the negative effects of visual distraction caused by a chromatic tuner by comparing NP and NBP between the visual and haptic groups.

To count NP, we used a visualized waveform of played sound and then double-checked the number by watching the video. To count NBP, we hired six student string players, taught right postures with beginner-level textbooks, and asked them to examine the posture of the participants recorded in the videos. Each video was probed by two reviewers, and their averaged count was used as NBP.

After the experiment, participants had an interview with the experimenter. They answered five questions in a 7-point Likert scale as to the adequacy, accuracy, helpfulness of feedback, the easiness of maintaining good posture, and the perceived degree of skill improvement. Participants also freely described their experiences about the experiment.

IV. Results

A. Learning Effects

Figure 7 shows the mean APEs and the mean NMPs measured in the pretest, the daily pretest and posttest of the five-day practice sessions, and the post test. The effectiveness of the two pitch correction methods can be assessed by comparing the mean APEs and the NMPs measured *without feedback* in the pretest and posttest. The mean APE decreased from 19.97 cents to 16.59 cents (17% improvement) with the visual group and from 20.13 cents to 14.53 cents (29%) with the haptic group. The mean NMP decreased from 10.67 to 3.78 (65%) and from 11.22 to 2.44 (78%) with the two groups, respectively.

The above results suggested greater performance improvement with HapTune than with the chromatic tuner. For confirmation, we performed two-way ANOVA with test and feedback method (subject group) as independent variables. The difference between the pretest and posttest was significant for both APE and NMP ($F(1, 32) = 21.26, p < 0.001$ and $F(1, 32) = 20.91, p < 0.001$). However, the difference between the two feedback methods was not significant for either measure ($F(1, 32) = 0.949, p = 0.337$ and $F(1, 32) = 0.052, p = 0.822$) or their interaction term ($F(1, 32) = 1.314, p = 0.260$ and $F(1, 32) = 0.304, p = 0.585$). The experimental data had very large individual differences as indicated by the 95% CIs shown in Figure 7. This behavior frequently appears in experiments that involve learning of complex cognitive-motor skills.

The learning curves of the two participant groups can be seen from the intermediary data in Figure 7 collected *with feedback* during the five-day practice sessions. During practice, the performance of the visual group was slightly better than the haptic group consistently in both APE and NMP. A three-way ANOVA showed that practice session was a significant factor for both APE and NMP ($F(4, 64) = 11.77, p < 0.0001$ and $F(1, 16) = 10.07, p = 0.0059$), indicating good learning effects over the five-day practice. A significant difference was also found between the daily pretest and posttest in both measures ($F(4, 64) = 10.89, p < 0.0001$ and $F(1, 16) = 8.21, p = 0.0112$). This implies that the practice was effective even within each day. However, feedback method was not significant for APE ($F(1,16) = 0.423, p = 0.525$) or NMP ($F(1,16) = 0.347, p = 0.564$). No two-way interaction terms were significant.

The results of the visual group suggested that their performance degraded in the final posttest (no feedback) compared to the daily posttest of the last day (feedback present). In contrast, the haptic group exhibited consistently improved performance even in the final posttest. As a consequence, the haptic group showed better performance in the posttest, though not statistically significant, than the visual group.

B. Negative Effects

The experimental data for NP and NBP are shown shown in Figure 8. The mean NPs ranged from 1.67 to 9.78. The plot clearly suggested that using the chromatic tuner increased NP substantially (compare the mean NPs with and without feedback). Using HapTune did not show such a tendency. As a result, the visual group showed larger mean NPs than the haptic group during the five-day practice sessions. The mean NBPs showed generally similar results. However, their range was very small (0.56–3.78), so observations drawn from NBP may not be as robust. Overall, the chromatic tuner seems to have caused more frequent distractions than HapTune.

Two-way ANOVA showed that the difference between the pretest and posttest was significant for NP ($F(1,32) = 6.23, p = 0.0179$), but not for NBP ($F(1,32) = 1.643, p = 0.209$). Feedback method was not significant for either NP ($F(1,16) = 0.249, p = 0.621$) or NBP ($F(1,16) = 2.454, p = 0.127$), nor was the interaction term ($F(1,32) = 0.003, p = 0.956$; $F(1,32) = 0.081, p = 0.778$).

We also conducted three-way ANOVA on the NP and NBP data of the five-day practice sessions. Practice session was significant for NP ($F(4,64) = 4.58, p = 0.0023$) but not for NBP ($F(4,64) = 1.93, p = 0.116$). Each day practice (comparison between daily pretest and posttest) showed the same results: significant for NP ($F(1,16) = 2.72, p = 0.119$) but not for NBP ($F(1,16) = 0.002, p = 0.969$). Feedback method was not significant for either NP or NBP ($F(1,16) = 1.97, p = 0.179$; $F(1,16) = 2.12, p = 0.165$). There were no significant two-way interaction terms.

C. Subject Responses

The results of the post-experimental survey are shown in Figure 9. The mean scores were generally high. The mean scores of the chromatic tuner and HapTune were 5.67 and 5.56 for the adequacy of feedback, 5.67 and 6.33 for the accuracy of feedback, and 6.33 and 5.78 for the helpfulness of feedback. It is interesting that the perceived accuracy was higher for HapTune than the chromatic tuner with a considerable difference (0.66), but the perceived helpfulness showed the opposite result (difference 0.55). The mean scores for the easiness of maintaining good posture were 5.33 and 5.78, and those for the perceived degree of skill improvement were 5.44 and 5.89. All these four scores were high, but HapTune resulted in greater scores than the chromatic tuners. We conducted a Wilcoxon signed rank test for each question,

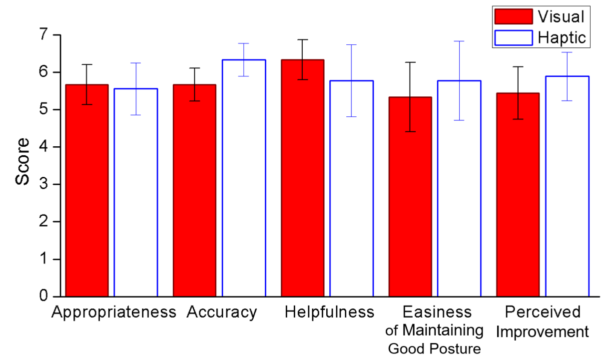

Fig. 9. Likert scale subjective responses to the questionnaire. Score 1 is the most negative score, and 7 is the most positive.

but none of them showed a significant difference between the two tuners ($W_{8,0.05} = 26$; $W = 5, 20, 10, 11$, and 9).

The participants reported that HapTune could provide accurate and intuitive haptic feedback. They also mentioned that just a few hertz of frequency differences in the played pitch led to strong vibration feedback and it felt uncomfortable although they were aware that it was for pitch correction. The participants evaluated visual feedback from the chromatic tuner to be easy to understand but visually distracting and sometimes confusing. Four participants in the visual group said that they had occasional trouble in reading the score, but only one participant complained the same in the haptic group.

V. Discussion

A. Effectiveness of Learning

In general, the acceptable level of pitch error is about 10 cents for expert string players [16]. The initial APEs of our participants were close to 20 cents (the pretest in Figure 7), but the five-day practice improved the APEs to 16.59 cents for the visual group and 14.53 cents for the haptic group, both with statistical significance (the posttest in Figure 7). Although these final APEs did not reach the acceptable level, they are sufficient to demonstrate the effectiveness of the two pitch correction methods.

Whereas the initial APEs (19.97 and 20.13 cents) were similar between the visual and haptic groups, the final APEs (16.59 and 14.53 cents) showed a noticeable difference (2.06 cents). The difference was not statistically significant, but it was as large as the pitch discrimination threshold of musicians (0.13% of frequency; 2.19 cents) [18]. A similar observation can also be drawn for NMP (initial values 10.67 and 11.22 and final values 3.78 and 2.44).

The performance of the visual group was noticeably degraded in the final posttest (measured without feedback) compared to that of the last daily posttest (measured with feedback right before the final pretest). In contrast, the haptic group's performance improved consistently. These results may be accounted for by the guidance hypothesis in motor learning [19]: augmented feedback with guiding properties can make the learner depend on feedback excessively as if the feedback were part of the task, and the performance may deteriorate when such feedback is not available [20]. The visual feedback provided by the chromatic tuner delivered detailed, clear, and exact information as to the played pitch, target pitch, and pitch error. This visual information might have been excessive and delayed the participants in developing their own skills for pitch correction (comparing the played and target pitches and adjusting the finger positions accordingly). However, the information presented by HapTune was limited to the nine discrete categories of pitch error (Figure 3 and Table I) with nothing about the played or the target pitch. The haptic information could have been closer to the "optimal" augmented feedback.

B. Negative Effects

Pauses and bad postures can occur for several reasons while playing a string instrument. However, comparison between the visual and haptic groups in terms of NP and NBP may reflects the effects of visual distraction caused by the chromatic tuner since the other conditions were identical. NP and NBP were indeed higher with the visual group than with the haptic group during practice (Figure 8). The differences, however, were not statistically significant, and NP and NBP were similar between the two groups in the final posttest. Therefore, it appears that chromatic tuners, which require visual attention, intensify negative effects during practice, but such effects are not transferred and quickly disappear when the chromatic tuners are no longer used. Note that this result is not very decisive; longer term studies are necessary for more authoritative conclusions as to this issue.

C. Advantages and Limitations of HapTune

The major results of the user study presented so far show good potential of HapTune as an alternative of chromatic tuners. In particular, HapTune may offer a new way to visually-impaired players to learn string instruments. So far, most visually-impaired string players have practiced pitch correction by utilizing auditory cues such as sound error alarm or reference pitch. These methods can be less effective because the played pitch and the feedback are delivered through the same sensory channel. In contrast, HapTune does not interfere with the auditory channel.

HapTune also has some limitations. In particular, some participants pointed out that intrusive, frequent vibrotactile feedback made it difficult for them to concentrate on playing and also tended to make them tired more easily, which may limit the time of using HapTune. We plan to explore alternate stimulus designs providing more pleasant tactile experiences while not compromising the recognition performance. Other forms of tactile stimuli, such as tap and skin stretch, not necessarily vibration, also deserve consideration.

VI. Conclusions

In this paper, we presented a between-subjects user study that compared the effectiveness of visual and haptic guidance in learning pitch correction skills while playing a string instrument. The user study was carried out with 18 string instrument learners over six days using a standard chromatic tuner and our haptic tuner (HapTune). The latter provided nine vibrotactile stimuli to the user's upper and lower arms representing nine discrete categories of pitch error. Experimental results validated the effectiveness of both tuners in learning the skills for playing correct pitches. The results also suggested two additional possibilities that HapTune allows better transfer of the learned skills and that the negative effects of chromatic tuners quickly disappear after practice. Our future research will focus on these two hypotheses.

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