# AN EXPLORATION ON THE INFLUENCE OF VIBROTACTILE CUES DURING DIGITAL PIANO PLAYING

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## ABSTRACT

An exploratory experiment was carried out in which subjects with different musical skills were asked to play a digital piano keyboard, first by following a specific key sequence and style of execution, and then performing freely. Judgments of perceived sound quality were recorded in three different settings, including standard use of the digital piano with its own internal loudspeakers, and conversely use of the same keyboard for controlling a physics-based piano sound synthesis model running on a laptop in real time. Through its audio card, the laptop drove a couple of external loudspeakers, and occasionally a couple of shakers screwed to the bottom of the keyboard. The experiment showed that subjects prefer the combination of sonic and vibrotactile feedback provided by the synthesis model when playing the key sequences, whereas they promote the quality of the original instrument when performing free. Even if springing out of a preliminary evaluation, these results were in good accordance with the development stage of the synthesis software at the time of the experiment. They suggest that vibrotactile feedback modifies, and potentially improves the performer's experience when playing on a digital piano keyboard.

## 1. INTRODUCTION

For its versatility and diffusion in diverse musical styles, with the advent of electro-mechanics, electronics, and finally digital technology, the piano has been progressively re-designed and engineered in different forms mainly to make its portability easier. Although sounding quite different, siblings such as the Clavinet and Rhodes electric pianos were initially able to keep a certain flavor of the original instrument, and then to conquer their own niche in contemporary music. In the meantime the early digital piano keyboards had begun to revolutionize the musical instrument market, by making piano performances possible on small stages and at home, where it would be otherwise unpractical or impossible to set up the original instrument.

With the advance of technology, digital pianos have progressively increased in sound accuracy and fidelity of their keyboard's response. Current flagship products exhibit sounds and key mechanics that satisfy the performer completely, once taken into account the relatively minor cost, size and weight of the digital instrument compared to its mechanical counterpart. On the other hand, the issue of vibrotactile feedback has been still left largely unexplored, despite playing a fundamental role in the performance on a real piano.

In spite of the current psychological and applied research trend toward a more systematic inclusion of vibrotactile devices in musical interfaces [1, 2, 3], also thanks to the notable decrease in costs of the related actuation technologies, we found only few studies on the topic of vibrations in the piano. Among these studies [4] there are a computational solution for improving the vibrotactile feedback provided by the upright piano through adaptation of the keybed impedance toward the characteristic values of the grand piano [5], and signs of research activity advertised in the CCRMA web pages, on tactile feedback design applied to the keyboards based on previous research made by Chafe [6].

Performers traditionally experience vibrotactile feedback in digital pianos only as a by-product of the resident loudspeaker system. By transmitting vibrations across the instrument body during the sound reproduction, the loudspeakers are in fact responsible of providing some related cues to the player. Arguably, such cues cannot achieve the intensity nor resemble the quality of those originating from a real piano keyboard, when the soundboard resonates under the action of the strings.

At least one flagship product, the Yamaha AvantGrand digital piano (see `www.avant-grand.com`), augments sounds by means of an active vibration system. By enabling transducers located under the keyboard and behind the music stand, it promises to engage users in a full-body sensory experience during playing [7, 8]. Indeed, the multimodal perception of harmonic components across the whole human body has been recognized to increase the engagement and sense of presence in users [9].

**Figure 1**. Clavinova YDP-113.

In the case of the Yamaha product, all its design solutions concur to form an extremely faithful reproduction of the original instrument, including its visual appearance. Due to unavoidable contingencies, in our experiment we rather made use of a less sophisticated musical interface, in both visual and non visual sense. More precisely:

- we used a Yamaha Clavinova YDP-113, an inexpensive digital piano (see Figure 1) that provides internal loudspeakers, but also offers MIDI master keyboard functionalities;

- in alternative to the Clavinova sounds, we synthesized sonic and vibrotactile feedback in real time by means of a physics-based piano sound model running on a laptop.

Vision did not play an integrative role in the multimodal scene. In fact, due to the appearance of the Clavinova-based setup, subjects were constantly aware that they were *not* playing a real piano. Using this setup we were able to provide the subjects with different sounds, with and without vibrotactile feedback.

The results of our tests overall suggest that the subjective judgments on sound quality were influenced by the vibrotactile feedback. Furthermore, as shown in the following of this paper, an analysis of the individual judgments indicates that the tactile modality can improve the auditory perception of digital piano sounds. However promising, such results call for a more robust and systematic validation that is expected to become object of future research.

## 2. EXPERIMENT

The experimental hypothesis was that the vibrotactile feedback coming from the instrument keyboard had influence on the perceived quality of piano sounds.

### 2.1 Subjects

Nine subjects voluntarily participated in the experiment. Three of them were pianists, four of them were other instrument players, and two of them were non-musicians.


**Figure 2**. Monacor Carpower BR 25 shaker.

### 2.2 Setup and configurations

Instead of explicitly being involved in a vibrotactile evaluation task, subjects were asked to rate the sound quality associated to two different digital piano settings: in the former the Clavinova worked with its internal loudspeakers; in the latter, the Clavinova controlled a synthesis software running in real time on a Core 2 Duo Dell Latitude E6400 laptop, in its turn driving a pair of Genelec 2029BR external loudspeakers along with a pair of Monacor Carpower BR 25 shakers.

The shakers (one is shown in Figure 2) were screwed to the bottom of the Clavinova. They are able to transmit mechanical power to the body they are in contact with. As a side effect they also generate some sound, amounting to few dB of intensity level that adds to the loudspeaker emission.

In spite of a claimed active band in the range 30-300 Hz, we measured that the Monacor shakers in practice work up to a few kHz, hence covering sufficiently well the entire vibrotactile perceptual band in correspondence of the finger, in particular including its higher sensitivity region centered around 250 Hz [10].

As noted by Bank [11], the active range of the shaker is sufficient to excite all the components that can be perceived by the palm [12] during normal piano playing. Figure 3 shows examples of such thresholds in dashed lines for the notes $C_2$, $C_4$, $C_6$, and the $C$ chord $\sharp 2$.

The software running on the laptop implemented a recently developed physics-based model [13] for the synthesis of piano sounds. The model was configured to compute two sound signals in correspondence of the left and right part of the soundboard. These signals formed the output for the Genelec loudspeakers and, equivalently, for the shakers.

In their own admission, the professional "golden ears" working on its fine-tuning, at the time of the experiment the model was not yet well balanced in the higher octave range. Furthermore we did not apply any amplitude, nor spectral equalization to the signals feeding the shakers: such manipulations are needed to simulate the vibrotactile response of specific piano keyboards such as those investigated by Bank [11]. For our purpose, we just tuned the intensity level of the shakers based on the subjective impression of two expert piano players who helped realize

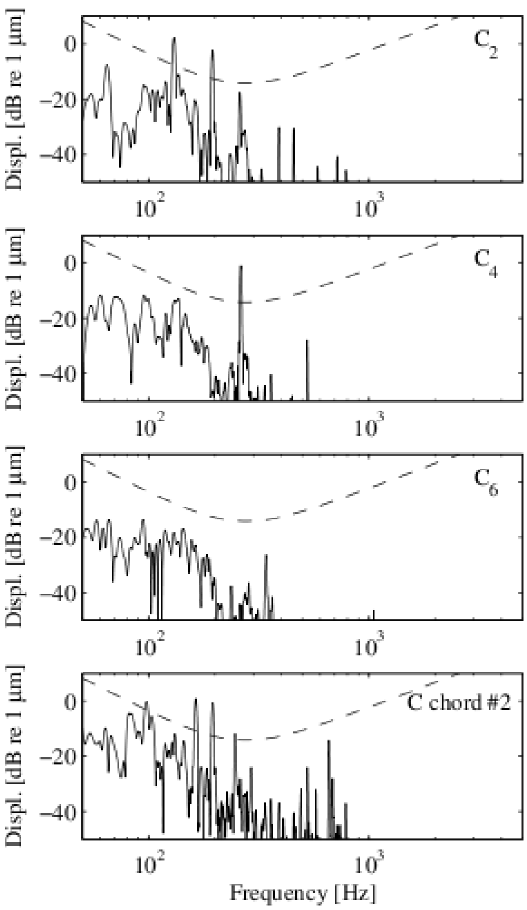


**Figure 3**. Spectra of the tactile response of a Bösendorfer grand piano measured at the keyboard (solid line), along with perceptual thresholds for the palm from Verrillo [12] (dashed line). Examples given for notes $C_2$, $C_4$, $C_6$, and the $C$ chord ♯2, all played at *forte* level.

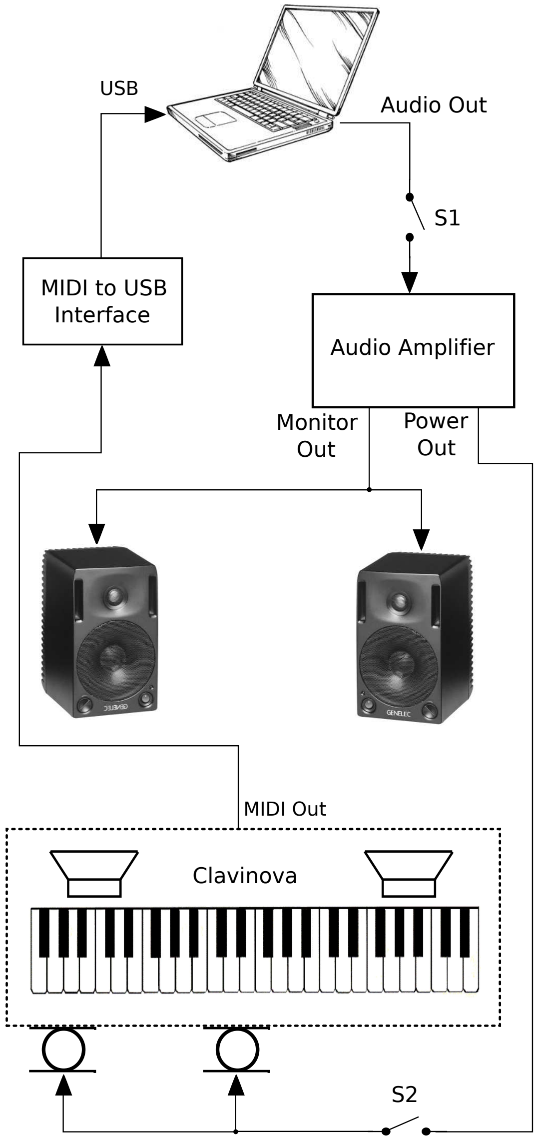


**Figure 4**. Experimental setup.

the experiment.

Figure 4 illustrates the experimental setup. Powered by a Pioneer A-225 stereo amplifier, the two shakers were respectively positioned under the leftmost and mid part of the keyboard. In this way they emitted energy in correspondence of the lower octaves, whose keys are mostly responsible of producing vibrations falling within the tactile perceptual band (see Figure 3).

Subjects were exposed to three possible experimental configurations—refer also to the positions of the switches S1 and S2 in Figure 4:

C: Clavinova only (Clavinova speakers on; S1 off);

M: physical model with Genelec (Clavinova speakers off; S1 on; S2 off);

MS: physical model with Genelec and shakers (Clavinova speakers off; S1 on; S2 on).

The intensity levels were equalized so as to minimize the overall loudness changes across the three configurations, i.e., by setting the level of C midway M and MS. As a result, we measured Sound Pressure Levels (SPL) between 69 dB(A) (configuration M) and 71.5 dB(A) (configuration MS), with configuration C lying between the two. At any moment, by operating on the amplifier and by turning up or down the main volume of the Clavinova to predefined levels, the experimenter could easily switch between the different configurations. Subjects were not informed about the presence of the shakers below the keyboard, nor obviously about the fact that these devices could be switched on and off during the experiment.

### 2.3 Task

Subjects were initially asked to play the keys $F$, $G$, $A$, $B$ of the lower four octaves (numbered 1, 2, 3 and 4 starting from the left side) in both directions. In more detail, they had to perform four tasks: playing i) an ascending *staccato* using only their right forefinger, ii) an ascending *legato* using at each octave the first four fingers of their right hand, iii) a descending *staccato* using only their right forefinger, and iv) a descending *legato* using at each octave the first four fingers of their right hand. The ascending patterns were performed by moving upward across the keyboard, conversely the descending patterns were performed starting from the fourth octave down to the first one. The sixteen hot keys were marked with a red pencil to help unpracticed piano players accomplish the task without effort.

In addition to the tasks explained above, subjects with self-reported sufficient ability to play the piano were invited to perform freely on the instrument, for instance by playing one of their preferred songs.

### 2.4 Method

The four tasks were repeated three times across the different configurations C, M and MS, for a total of $4 \cdot 3 \cdot 3 = 36$ randomized *short* trials for each subject. This part of the experiment took about 35 minutes. Additional 15-20 minutes were required by the pianists to accomplish the free performance in the three configurations C, M and MS, summing to three additional *long* trials for these subjects.

At the end of every short trial, subjects marked the perceived sound quality on a scale ranging from 1 (very low) to 7 (very high). Long trials were instead judged qualitatively by the pianists. At the end of the experiment, the subjective skill in playing the piano was rated (1 to 7) along with the difficulty in performing the task (low, medium, high, very high). Only one subject reported a medium difficulty in performing the task, all the rest of the group otherwise rated the task difficulty to be low.

## 3. RESULTS

The aggregation of the judgments given by all the subjects during the short trials provides three sets of $4 \cdot 3 \cdot 9 = 108$ ratings, each set corresponding to a respective configuration. The mean values respectively amount to 3.741 for C, 3.981 for M, and 4.185 for MS (last row of Table 1).

A repeated-measures ANOVA conducted on the subjects' average ratings under the three configurations states that the mean values are significantly different at a 2% significance level: $F(2, 8) = 3.44$, p $= 0.017$. A similar analysis, made by restricting the attention to couples of such sets, shows that the difference is significant for both M and MS ($F(1, 8) = 15.46$, p $< 0.001$) and C and MS ($F(1, 8) = 3.44$, p $< 0.017$), wheras it is not significant between C and M ($F(1, 8) = 1.89$, p $= 0.19$). Furthermore, t-tests pairing the subjective judgments across the different conditions show $p$-values respectively equal to $p_{\mathrm{C}\leftrightarrow\mathrm{M}} = 0.176$, $p_{\mathrm{C}\leftrightarrow\mathrm{MS}} = 0.015$, and $p_{\mathrm{M}\leftrightarrow\mathrm{MS}} = 0.256$, with obvious meaning of the subscripts of $p$.

Concerning the free performance, the three pianists respectively opted for playing a pop song by the Beatles, an improvised jazz tune, and a *preludio* by Bach. All of them had a strong preference for the C configuration.

## 4. DISCUSSION

The different judgments existing between the single key patterns and free performance were almost certainly affected by the limited accuracy of the physical model in the higher octaves. It seems clear that as soon as the pianists heard a degradation of the sound quality, the vibrotactile modality lost any significance in their subjective judgment, and consequently the physics-based model was downgraded in their judgments.

| Mean Values | | | |
|---|---|---|---|
| **Subject** | **C** | **M** | **MS** |
| Pianists | | | |
| 2 | 4.000 | 5.000 | 5.167 |
| 5 | 3.833 | 5.000 | 5.250 |
| 8 | 4.084 | 2.333 | 2.083 |
| Other Musicians | | | |
| 1 | 4.083 | 5.250 | 5.083 |
| 4 | 2.833 | 3.500 | 2.917 |
| 7 | 5.667 | 4.167 | 4.333 |
| 9 | 3.750 | 3.750 | 4.250 |
| Non Musicians | | | |
| 3 | 3.000 | 3.500 | 4.250 |
| 6 | 2.417 | 3.333 | 4.333 |
| Aggregate | | | |
| All | **3.741** | **3.981** | **4.185** |

**Table 1**. Mean values for the different configurations, by subject plus aggregate.

Conversely, the results obtained by judgments on single notes ranging in the lower four octaves reveal that the vibrotactile feedback adds discrimination in the otherwise not significantly different judgment of the physics-based sound against the Clavinova samples.

However encouraging, the result on the aggregate data becomes less dramatic if reported on an individual basis. In fact, if we analyze the significance of the different configurations subject-by-subject then we discover that, once taken individually, subjects tend to grade the configurations mainly by their sound, and rarely the difference between M and MS gains significance.

Figure 5 shows, using double-sided arrows, subject-by-subject significance of the differences between configurations, obtained by computing t-values of the corresponding paired data at 5% significance level. The aggregate result presented in Section 3 is shown as well, at the bottom of the same figure.

From this figure, along with a look at the subjective mean values listed in Table 1, it can be observed that pianists seem to fairly weigh the vibrotactile modality, and rather base their judgments on robust decisions informed by the auditory modality—indeed, the question to the subjects was exactly that of rating the quality of the sound. As we move toward less specialized listeners, i.e. other instrument players, the corresponding mean values and related significances become more variate, including those of two subjects who do not appreciate any significant difference among the experimental configurations. Finally, non-experienced subjects exhibit less common judgments, including one subject who finds significant differences between M and MS.

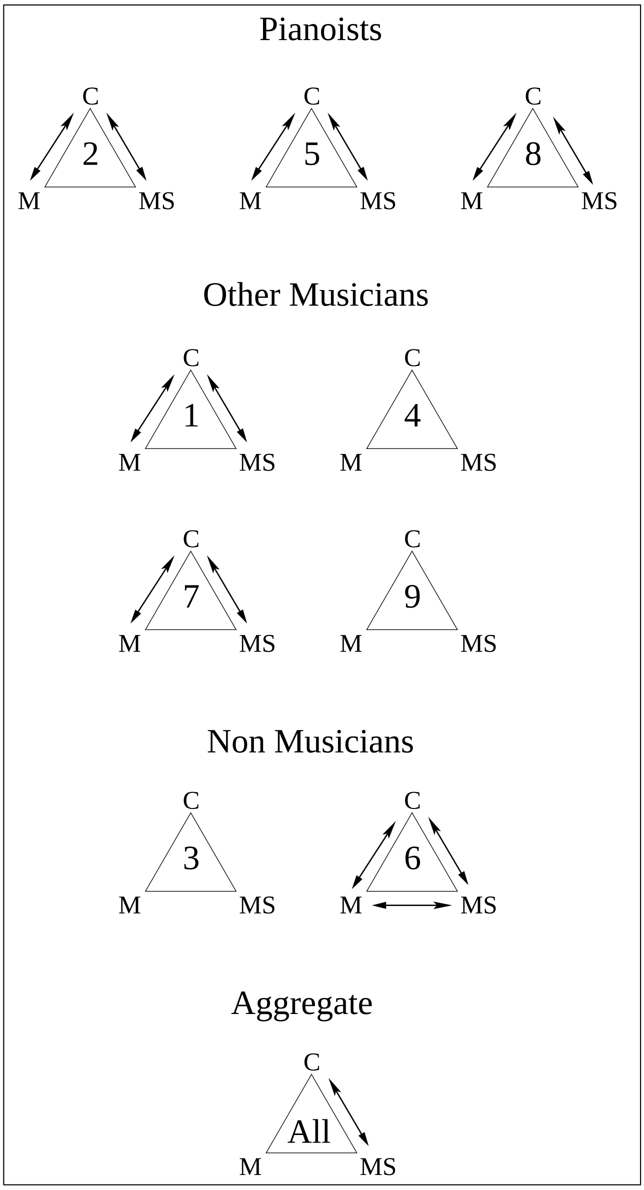


**Figure 5**. Significance of judgments, by subject plus aggregate. Double-sided arrows connect configurations whose different judgment is significant at 5% level, according to t-tests pairing the corresponding data. Subject number written at the center of the corresponding triangle.

Even if the number of subjects populating the different categories is too scarce to signify anything, a possibly relevant case record can be inferred from the subject-by-subject analysis. Specifically there may be a trend, potentially indicating a decreasing importance of the vibrotactile feedback for subjects who have more familiarity with musical sound evaluations, with minimal significance of the tactile modality for pianists. On the other hand, the results of non-experienced subjects may suggest that physically-consistent vibrotactile feedback can help unpracticed users enter into contact with musical interfaces such as keyboards, whose complexity of use is well known by practitioners.

In summary, the proposed experiment represents a first, far from being exhaustive attempt to understand the importance of vibrotactile cues in digital piano playing. Furthermore, it shows limits in setup and methodology. Contingent difficulties for the experimenter in recruiting a sufficient number of subjects with different musical skill levels, together with the impossibility (due to limits in manpower) to prepare two acoustically different physics-based piano models having comparable sound quality, prevented to include a control session in which subjects could compare two models without vibrotactile feedback. Were musicians biased by the assumption that the vibration of a digital piano keyboard could not be changed during the tasks, or was the vibrotactile feedback equalized too roughly to elicit a definite sensation of quality improvement in pianists, are just two among the many questions that cannot be answered using our data.

## 5. CONCLUSIONS

In an experiment where subjects, after playing a digital piano, had to rate two different instrument models, we investigated the salience of vibrotactile cues as potential enhancers of the sound quality. Specifically, the test was made by switching on and off two shakers while subjects were performing a task with the latter model. Conversely, the former was played without any modification of its vibrotactile feedback.

Results say that, overall, the inclusion of the vibrotactile modality adds a significant improvement to the quality of the sound of the latter model. An analysis conducted subject-by-subject suggests that differences exist among the individual judgments on the same models, without a specific preference for the configuration enabling the vibrotactile feedback.

A classification of the subjects based on their knowledge of musical instruments, specifically the piano, was postulated to investigate musical skill as a possible predictor of preference. In the limits of the low number of subjects forming the three resulting classes, the subjective analyses indicate that pianists may be only weakly (albeit not significantly) influenced by the vibrotactile augmentation when making judgments on sound quality, whereas other musicians and non-musicians may be influenced more. Nevertheless, this conclusion is purely tentative at this stage of the experimentation.

Encouraged by this experience, we are planning to follow up with a more robust setup and overall experimental design. Concerning the setup, we will operate an equalization of the signals from the shakers meanwhile providing all the conditions for comparing configurations, in which the control of the auditory and vibrotactile feedback will be completely independent and orthogonal. Concerning the experimental methodology, new subjective tasks will be designed allowing for the extraction of more reliable figures of sound quality and realism of the overall experience.

**Acknowledgments**

The research leading to these results has received partial funding from the Joint Project E-PHASE, participated by the University of Verona and Viscount SpA, and from the

European Community's Seventh Framework Programme under FET-Open grant agreement 222107 NIW - Natural Interactive Walking.

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