# Perception of Interactive Vibrotactile Cues on the Acoustic Grand and Upright Piano

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## ABSTRACT

An experiment has been conducted, measuring pianists' sensitivity to piano key vibrations at the fingers while playing an upright or a grand Yamaha Disklavier piano. At each trial, which consisted in playing loud and long A notes across the whole keyboard, vibrations were either present or absent through setting the Disklavier pianos to normal or quiet mode. Sound feedback was always provided by a MIDI controlled piano synthesizer via isolating ear/headphones, which masked the acoustic sound in normal mode. In partial disagreement with the existing literature, our results suggest that significant vibrotactile cues are produced in the lower range of the piano keyboard, with perceptual cut-off around the middle octave. Possible psychophysical mechanisms supporting the existence of such cues are additionally discussed.

## 1. INTRODUCTION

As the importance of multisensory perception of musical instruments by the performers is progressively being uncovered [1], specific research is investigating the role of haptic feedback in conveying additional cues representative of the instrument to the performing musician. Such research covers quantitative aspects, with special regard to the vibrations transmitted to pianists and violin players [2, 3] by their instruments, until spanning the emotional [4] and affective [5] correlates coming from feeling vibrotactile cues while being engaged in a musical performance.

Specifically concerning the piano, keyboard makers have long since given empirical evidence of the importance of haptic cues in defining the quality of an instrument. First of all *touch*, mostly depending on the keys' material along with their dynamic response due to the connection mechanism with the strings, confers a unique haptic signature to a piano [6]. For instance, Galembo and Askenfelt showed that a blindfolded group of expert pianists easily recognized three previously played different pianos by randomly performing over them. Conversely they lost much of their own recognition ability when just listening to the same pianos [7]. Haptic-enabled keyboard prototypes have been described in e.g. [8, 9, 10], in which the authors highlighted that the haptic response at the fingers carries valuable information for the pianist. More recently, Yamaha Corp. has equipped its flagship AvantGrand digital piano line with vibrational transducers, aiming to reproduce the vibrotactile feedback that pianists experience while playing the real instrument [11].

Nevertheless, currently the relationships between the perceived quality of a piano and the haptic signature of its keyboard have been understood only to a limited extent. It is generally acknowledged that the use of a simplified keyboard mechanics along with keys made of plastic material, such as those found in consumer digital pianos, inevitably translate to a less rewarding experience for the pianist. Yet, the subjective effects of an impoverished keyboard on the perceived sound quality have not been quantified to date. Even less is known about if and how the same quality is influenced by vibrotactile feedback arriving at the pianist's fingers once the more prominent somatosensory experience of striking the keys has ceased, leaving space to the vibrations traversing the instrument until the keys are released. In a related study [12], some of the present authors conducted a pilot experiment on a digital piano modified with the addition of vibrotactile feedback. The experiment tested the perceived sound quality in different settings: i) original digital piano; ii) use of a physics-based piano synthesizer for external audio feedback; iii) use of the same synthesizer for both audio and vibrotactile feedback. The subjects preferred the combination of audio and vibrotactile feedback provided by the piano synthesizer when playing key sequences, whereas they promoted the quality of the original digital instrument when performing freely. Although preliminary, 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.

On the other hand, while investigating the perception of vibrations on a grand piano, Askenfelt and Jansson [2] provided quantitative evidence that even *ff* notes generate partial components whose magnitude hardly exceeds the known vibrotactile thresholds at the fingers [13]. This is true even when those partials fall within the frequency range where this sensitivity is highest [14]. Their measurements, hence, support the claim that neither a piano keyboard nor the keybed or the pedals should be able to convey prominent vibrotactile cues to the pianist.

Nevertheless, the above mentioned thresholds were measured with sinusoidal vibratory signals, while lower thresholds may be expected for more spectrally rich signals. Moreover, pianos convey to the performers sensations going beyond the perception of steady vibrotactile signals. The pianist is in fact engaged in an enactive experience where every key depression produces a distinct audio-haptic contact event, immediately followed by the transmission of vibrotactile cues from the keyboard, caused by the vibrating strings and resonating body of the instrument. Such cues are subjected to disparate temporal, spatial and spectral summation or interference effects, depending on the sequence of played notes and chords, as well as on the position of the hands on the keyboard. For all such effects the literature provides only sparse data, furthermore measured in non-musical, especially laboratory setups [15]. Indeed, Keane and Dodd [6] assumed that pianists perceive vibrations while playing, and studied how professional pianists rated different upright pianos according to the perceived vibration intensity. The model offering less vibration (i.e. the one with a stiffer keybed) was preferred. The authors however noted that the players generally did not pay conscious attention to touch and key vibrations.

In this study we hypothesize that performers perceive vibrotactile cues of musical notes through their fingers while playing. In our experiment, two independent groups of pianists have been exposed to vibrations from the keyboard while playing notes respectively on a grand and an upright piano, both giving the possibility to switch the vibrotactile feedback on and off across trials, meanwhile keeping the auditory feedback constant. The results from the tests suggest the existence of significant differences between the condition with and without vibrations, for both setups.

## 2. TECHNICAL SETUP

The experiment made use of two Yamaha Disklavier pianos, a grand model DC3 M4 (setup in Padova, "PD" hereafter) and a upright model DU1A with control unit DKC-850 (setup in Zurich, "ZH" hereafter), offering a switchable "quiet mode" that allows their use as silent MIDI keyboards. In this configuration the hammers are prevented from hitting the strings, and therefore the piano does not resound nor vibrate, while the keyboard mechanics is left unaltered.

**Figure 1**: Setup for loudness estimation on the grand piano (PD) using a KEMAR mannequin.

Since the experiment aimed to investigate the perception of vibrotactile cues at the keyboard while playing, we took advantage of the switchable quiet mode to either provide vibrations or not. In order to uniform these two experimental conditions (vibration ON/OFF), subjects had to be prevented from hearing the acoustic sound of the Disklavier when set to normal configuration (i.e. the "vibration ON" condition). Therefore, the MIDI data provided by the Disklavier pianos were used to control a high quality software piano synthesizer [1] that was configured to simulate a grand (PD) or a upright (ZH) piano. The synthesized sound was provided by means of isolating headphones Sennheiser HDA-200 (PD) or earphones Shure SE425 (ZH). In the latter case, earmuffs 3M Peltor X5A were worn on top of the earphones to maximize sound isolation.

The loudness of the acoustic pianos at the performer's ear was estimated by recording with a KEMAR mannequin all the A keys played at various velocities (Figure 1 shows the PD setup). Then, the dynamic response of the piano synthesizer was matched to those of the corresponding acoustic piano, by performing similar measures on the KEMAR mannequin equipped with the corresponding headphones. Informal testing proved that in this configuration the acoustic sound of the piano was fully masked, and no difference could be perceived in the heard sound in the two conditions.

The pedals were made inaccessible and were not used in the experiment. The wheels of the pianos (instrument-floor contact points) were placed on stacks of rubber-foam layers, while the stools and pianists' feet were isolated from the floor by means of thick rubber panels, in this way preventing the subjects to feel vibrations via anything but the fingers. The two setups are shown in Figure 2.

The software piano synthesizer ran on a laptop computer, and a RME Fireface 800 audio interface was used to collect MIDI data from the Disklavier pianos and provide audio feedback. The experiment was run under human con-

[1] Modartt Pianoteq 4.5. See `www.pianoteq.com`.


**Figure 2**: Disklavier setups. Top: Yamaha DC3 M4 (PD). Bottom Yamaha DU1A (ZH).

trol with the help of a software developed in the Pure Data environment. The program allowed to read playlists describing the series of randomized trials (e.g. A4, vibration OFF), and record answers for each subject. The quiet mode of the Disklavier pianos was remotely switched at need via automatic software control. At each trial, a correctness test was performed to check on the played note and velocity (see Section 3 for more details).

## 3. EXPERIMENTAL PROCEDURE

The test was a yes-no experiment. The task was to play a loud, long note (*mf* to *fff* dynamics, lasting 4 metronome beats at 60 BPM) and then to report whether vibrations were present or not, respectively by saying aloud "yes" or "no". The subjects were instructed to focus on the feeling at the flesh of the fingertip during the steady-state part of the sound. They were also told that the vibrations could be turned on and off and therefore saying "yes" to everything would lead to an increased number of incorrect responses.

Only the A keys across the whole keyboard were considered, in this way reducing the experiment's duration while maximizing the investigated pitch range, from the leftmost key of the piano keyboard to near its right end. The 8 A keys were labeled with numbers (1=A0 .. 8=A7) in order to minimize the chance of execution errors. Keys 1-4 (A0-A3) were played with the left index finger, and keys 5-8 (A4-A8) with the right index finger.

A randomized sequence of 128 trials was provided, made up of 16 occurrences of each A key. Half of the trials were in the "vibration OFF" condition, corresponding to the Disklavier set to quiet mode.

The participants were asked to sit at the piano and instructed on the procedure. They were explicitly told to pay attention to the keys vibrations while playing, and not to take into consideration any tactile cue until a key had reached the keybed.

Before starting, the subjects wore the provided isolating headphones (PD), or earphones and earmuffs (ZH). As reported in Section 2, in this configuration they could only hear the piano synthesizer sound, while the original sound form the Disklavier (if present, i.e. only in normal mode) was masked.

At each trial, a voice prompt signaled which A key to play (numbers 1-8), and right after a metronome started.

The MIDI velocity provided by the Disklavier was checked against the velocity range 73-127[2] by our data acquisition software: when playing with insufficient strength, the participants were required to repeat the trial. The software also checked whether the right key had been played.

After giving their judgment, the participants had to remove their hands from the keyboard, in this way preventing them to feel the mechanics switching the Disklavier from/to quiet mode between the trials. The total duration of the experiment was about 20 minutes per participant.

Two distinct groups of nine subjects participated in the grand (PD) and upright (ZH) piano experiments, respectively. The participants in the PD experiment were males, average age 32 years. In the ZH experiment, the average age of the participants was 37 years and three of the subjects were females. Most had at least intermediate piano skills, one at professional level, while three subjects had practically none.

## 4. RESULTS

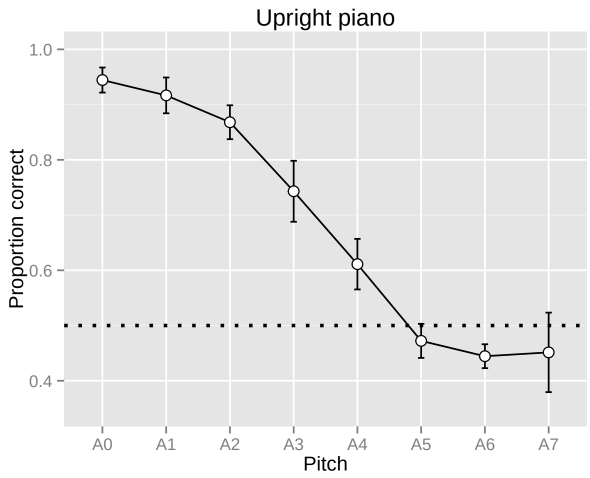
Proportions of correct responses, given by

$$p(c) = \frac{\text{hits} + \text{correct rejections}}{\text{total trials}},$$

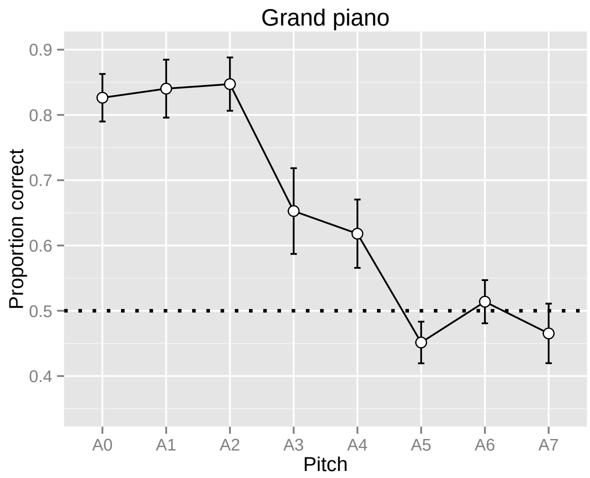
where hit = "yes" response when vibrations were present, and correct rejection = "no" response when vibrations were not present, were calculated for each participant individually for each A key. Average results for the upright and grand configurations are presented respectively in Figures 3a and 3b, showing a similar trend. For the lowest three pitches (A0 to A2), the subjects could easily discriminate between the trials with and without vibrations. In the middle register the proportion of correct responses was still over 60%, while it finally dropped to chance level at A5 ($f_0 = 880$ Hz).

A sensitivity measure of detection theory $d'$ [17], estimating the strength of a signal given the separation and spread of the distributions of inner responses when the signal (vibrations) is either present or not, was computed for the up-

[2] Approximately corresponding to dynamics from *mf* to *fff*.




(a)




(b)

**Figure 3**: Mean proportions correct for the upright (a) and grand (b) piano configurations. Chance performance given by dashed line. Error bars present within-subjects confidence intervals according to [16].

right piano and for each individual separately according to

$$d' = z(\text{hits}) - z(\text{false alarms}),$$

where $z$ signifies Gaussian $z$ transformation and hits = proportion of "yes" responses with vibrations present and false alarms = proportion of "yes" responses with vibrations absent. The individual $d'$ estimates, however, suffer from increasing statistical bias with low numbers of vibrations present and absent trials (8 each). Furthermore, the frequent occurrence of 0 and 1 proportions at low pitches, where the task was easy, calls for adaptations of the proportions in order to avoid infinite $d'$. Therefore, individual proportions were pooled within groups of subjects who shared a reasonably similar individual sensitivity $d'$ and decision criterion $c$, given by [18]

$$c = -1/2 * [z(\text{hits}) + z(\text{false alarms})]$$

A group $d'$ was estimated for each pitch as an average of 2-3 such groups in order to achieve a measure less biased than a simple average of all individual $d'$s. The subjects could be roughly divided into two main groups according to their behavior. One group of subjects had a tendency to say "no" in the low range, where discrimination was easy, and to say "yes" more likely in the high range where discrimination was practically impossible. They seemed to aim at a more even rate of positive and negative responses over the whole pitch range, while the second group had an opposite strategy. The subjects from the second group had a tendency to say "yes" in the low range and "no" in the high range, as if they had drawn the conclusion that there were no "yes" cases available in the high range and, to compensate, lowered their criterion in the low range.

The estimated $d'$ is presented as a function of pitch in Figure 4. Similarly to the proportions correct, the group $d'$ drops to chance level at A5 and is about 0.5 at A4. From A0 to A3 $d'$ drops from high to moderate sensitivity ($d' = 1$ corresponds to 69% correct). The criteria and sensitivities were more varied in the grand piano configuration and individuals were not easily grouped for pooling proportions to estimate a group $d'$. Further analysis is therefore based on proportions correct.

The cut-off point for perception of key vibrations seems thus to be somewhere above A4 ($f_0 = 440$ Hz). The distributions of individual proportions correct for grand and upright pianos were statistically tested at that pitch. The Kolmogorov-Smirnov test supports the hypothesis that both distributions share a same location ($D = 0.111$, $p = 1$), so the distributions were combined. The resulting distribution (sample $\mu = 0.615$ and $\sigma^2 = 0.032$) was tested for normality by the Shapiro test ($W = 0.926$, $p = 0.164$), indicating that the joint distribution could be roughly normal. The 95% confidence interval for the joint mean was found by a t-test to be [0.525, 0.704]. Since chance level ($p(c) = 0.50$) is just outside the confidence interval, it was concluded that key vibrations are still perceivable at A4. At that pitch, exactly 50% of the subjects were successful at discriminating between the vibration ON and OFF trials, with a minimum $p(c) = 0.69$ and mean $p(c) = 0.771$. At A5, only one subject exceeded chance level ($p(c) = 0.62$). Finding a more precise cut-off point is left for a future experiment.

## 5. DISCUSSION

Askenfelt and Jansson measured piano key vibrations [2] and concluded that they exceed the detection threshold (measured by Verrillo [13, 14]) only in a narrow range around 200 Hz, where the human sensitivity to vibrotactile stimulation is highest. Our findings contradict those results especially in the low range up to 110 Hz, where detection was clearly easier than in the range of highest sensitivity, where only two thirds of the subjects were successful at detecting key vibrations. This may be explained by the nature of the vibratory signal which was not sinusoidal, unlike in the threshold measurements by Verrillo. Generally lower thresholds have been reported for complex than sinusoidal signals in the palm area for stimuli above 250 Hz [15]. Other measurements have also revealed that

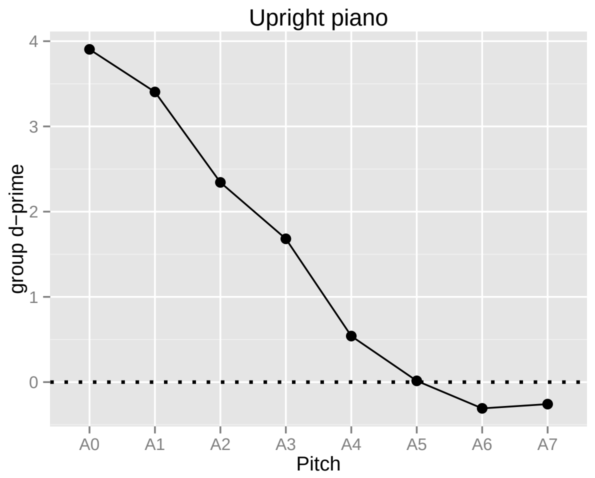



**Figure 4**: Group $d'$ for the upright configuration. Chance performance given by dashed line.

vibrotactile signals carry loudness, timbre and even pitch information [19, 20], so the vibration spectrum has obvious perceptual importance.

Human vibrotactile perception combines information from four psychophysical channels [21], the Pacinian channel (P) and three non-Pacinian channels (NP I, II, and III), whose frequency response overlaps partially. Thus vibrotactile thresholds depend on the sensitivity of each channel at a given frequency, and suprathreshold vibrations may activate two or more channels at the same time. The P channel is most sensitive around 250 Hz, while the NP I and NP II channels mediate lower frequency bands. The higher sensitivity in the lowest pitch range observed in the present study, could be caused by either relatively high energy in the frequency range of the P channel, or high vibration levels in the lower range, which clearly exceed the threshold of the NP channels. Moreover, in the frequency range for the P channel, spatial summation is known to lower thresholds. Verrillo showed that thresholds decrease by 3 dB by doubling of contact area in the range around 250 Hz but not in the lowest bands [13]. He however considered smaller contact areas as compared to our case, where areas could vary from the very tip of the finger, to the whole fingertip.

Cross-modal interactions between auditory and vibrotactile perception are a possible source of threshold changes, however contradictory results are found in the literature. For instance, Verrillo [22] reported that vibrotactile thresholds increase slightly in presence of a matching (and therefore masking) auditory stimulus, while Ro *et al.* [23] showed that sounds matching the frequency content of vibrotactile stimuli enhanced their perception.

Our study concerns active pressing, and the forces normally exerted by pianists over the keyboard range from 1 N (soft legato) to 50 N (*fff* staccato) [2]. The effects of active pressing force on vibrotactile perception are not thoroughly known, but there is evidence that vibrotactile magnitude sensation increases under a passive static force [24].

Motor locomotion studies have demonstrated that subsensory vibratory noise applied to the soles of the feet reduces gait variability and falls in elderly participants [25]. Such studies have also shown that, although not significantly, young participants improved their balance as well when their locomotion was supported by subsensory noise underfoot. The physical phenomenon at the base of these results is called *stochastic resonance*: noise makes weak signals occasionally achieve amplitude peaks that exceed the somatosensory system thresholds. At that point, the resulting vibrotactile sensation triggers the appropriate motor function [26]. Unfortunately, similar results have not been investigated in motor tasks involving the arms, hands and fingers. Nevertheless, each time a pianist strikes the keys (s)he receives a strong, broadband vibrotactile attack signal that progressively focuses, during decay, around the partial components of the played notes. In a suggestive hypothesis that our study cannot confirm, we speculate that not only does the attack component enable pianists to perceive otherwise sub-threshold vibrotactile stimuli – similarly to what stochastic resonance allows for – it may also help the performer increase her control over the hand motor task, and for this reason even influence the perceived quality of the instrument as a by-product of the consequent improvement in the musical performance.

## 6. CONCLUSIONS

Contradictory research results exist concerning the vibrotactile perception of notes from a piano keyboard. In fact, the related literature either assumes the existence of salient cues of vibration coming from the instrument, or is conversely skeptical about the ability of pianists to perceive such cues during playing. The experiment reported in this paper supports the former conclusion, limited to the lower part of the keyboard, for both upright and grand pianos.

Future experimental activities will be targeted at 1) investigating perception of vibrotactile cues under more general conditions (particularly exploring different dynamic ranges and different tone durations, as well as using a larger set of piano keys), and 2) understanding the role of vibrations in subjective assessments of perceived piano quality.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