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On the Characterization of Vibrotactile Feedback in Violinists' Left Hand: A Case Study

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Abstract
The long-term goal of this project is to investigate the differences in the "feel" of a violin that can be perceived through the left hand, across a certain range of instruments. The approach taken in this paper involves comparing amplitudes of vibration at the neck of several violins with violinists' sensitivity to vibration in their left hand. Absolute thresholds for vibration detection were measured on violinists holding an isolated vibrating violin neck, which allowed to simulate the real playing condition, in particular the pressure and the position of the hand on the neck. Using a standard alternative forced choice procedure, measurements were done as a function of frequency in the skin sensitivity range 200–900 Hz. Vibration levels of the necks were measured across a set of instruments, using a laser vibrometer and an impulse excitation at the bridge. Results show that the neck vibration levels are overall above the perceptual thresholds for most violins and at most frequencies below 900 Hz but the relative difference between the two curves can vary a lot from violin to violin. This comparison presumes the existence of vibrotactile feedback at the left hand as a potential perceived signature of the violin played.

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1. Introduction

A long-standing goal of violin acoustics research has been to better understand what contributes to the judgment of a violin's quality. However, it remains difficult to define how a measurable mechanical parameter relates to the instrument's perceived quality (e.g. [1, 2, 3]), in particular because of the challenge of interpreting physical measurements perceptually. Besides, many violinists consider that "an instrument must not only sound correct but it must also "feel" correct" [4]. Digital musical instruments research generally associates the "feel" of an instrument with the vibrations of the instrument and consistently showed the benefits of providing vibrotactile feedback to musical performers so that the "feel" of the instrument can be enhanced [5, 6, 7, 8]. Violin acoustics literature on the "feel", however, remains limited.

As in any traditional musical instrument performance where the musicians are in an intimate contact with their instrument, the violinists are simultaneously in the role of the actuator, exciting the complex structure to make it vibrate and radiate sound, and in the role of the first receiver of the violin's response. In addition to the auditory feedback, violinists receive vibrotactile feedback through different contact points – the left hand holding the neck, the right hand holding the bow, the chin and the shoulder – which enable them to adjust the control on the instrument.

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The feel of a violin, as opposed to its sound, is thus likely to be a combination of parameters related to the haptic comfort of the instrument (geometry, weight, ergonomics) and parameters related to the perceived response of the violin to the player's input (e.g. response under the bow, feeling of vibrations through different points of contact).

The few studies invoking that notion share a focus primarily on violin necks' vibrations, suggesting that when perceived through the left hand of violinists, these vibrations become the basis for the perception of how a violin feels. As an acoustician, Marshall [4] hypothesized that the principal vibrational modes of the neck of a violin play an important role in the way a violin feels in that they exist at low frequencies to which the human skin is sensitive ([0–1000] Hz): "it is highly likely that the "feel" of a violin is principally determined by the lowest order vibrational modes of the violin, and particularly those modes that exhibit strong participation by the neck fingerboard and/or corpus" (p.705).

In a second study, Marshall [9] investigated how the presence of the violinist (position of the left hand, chin and shoulder) influences the vibrational behavior of the instrument. According to him, there is a link between the damping of vibrations and their detection by the violinist. Indeed, several modes (in particular in the neck) tend to be damped in the held violin, but by holding it, the players detect the motion directly on the fatty skin. This detection gives rise to the perception of how "alive" the violin feels, many violinists preferring "alive" instruments:

"the greater the number of occurrences [where the left hand detects motions at antinodal portions of the neck], the more "alive" the violin will be judged by the performer" (p.1021).

Hutchins [10] and Woodhouse [11]) developed this research by exploring the coupling which potentially exists between the body modes of the violin (in particular the B0 mode, a bending mode of the whole violin body, neck and fingerboard) and those of the main air resonance A0, also called "Helmholtz mode". According to Hutchins, the frequency matching of the A0 and B0 modes can enhance the sensation of good "feel", desirable by many players as reflected in a reported anecdote of a violinist pleased to feel "his fingers surrounded by sound" when discovering a Stradivarius. She however does not conclude that it is a fundamental attribute for a good violin.

Woodhouse developed a simple two-degree-of-freedom model to investigate the coupling phenomena. He defined several transfer functions including a proper transfer function to "feel", which quantify the vibration levels at violin necks. He then discussed why A0/B0 matching could contribute to a good "feel" (the coupling enhances the vibrations perceived through the hand).

However, all these studies attempted to quantify the characteristics of the "feel" of a violin mainly from measurements of the violins' physical (acoustical and mechanical) properties. But such approaches neglect the perceptual aspects of the player-instrument interaction, which is essential in the performance of any traditional musical instrument. For that reason, we feel it necessary to extend this research by relating relevant vibratory measurements made on the violins to measures of physiology of the human haptic system.

To the best authors' knowledge, only one paper attempted to link psychophysics and acoustics to address this question. Askenfelt and Jansson [12] carried out a series of vibrational measurements on four stringed instruments – double bass, violin, guitar and piano – in a procedure that allowed levels of vibration recorded at different positions on the instruments and at different dynamics (from *p* to *ff*) to be compared with the skin vibration sensation threshold measured at the fingertip by Verrillo [13]. They provided potential evidence that the instruments' vibrations can be felt by players in playing situation since they experimentally observed that the instruments' levels of vibration were above the fingertip vibration sensation threshold for almost all positions on the instruments. In particular, they compared sideways vibration levels (hereafter denoted "horizontal" vibrations) recorded at 4 violin necks by means of a small accelerometer during normal playing with the vibration sensation threshold of the fingertip, as a function of frequency. They experimentally observed that the violin neck vibrations were above or very close to the sensation threshold in the skin sensitivity interval from 196 to approximately 1000 Hz.

From Askenfelt and Jansson's experiment [12], questions can be asked about what distinguishes perceptually one violin's vibratory response from another, otherwise stated, whether the perceived vibrotactile feedback is violin-dependent. More specifically, one can ask whether violinists could discriminate violins according to the vibration levels felt by their left hand only, across a certain range of instruments.

However, if we want to fully compare violins with respect to the vibration levels felt by the left hand, Askenfelt and Jansson's data are not sufficient for two main reasons. On the one hand, the vibration levels at the necks were measured while playing one note, so were only obtained at the harmonics of the note chosen (lowest G, 196 Hz). Since the study is limited to the skin sensitivity range [0–1000] Hz, the level curves thus consist of five points only. This makes discriminations among violins according to their levels of vibration limited. On the other hand, the vibration levels measured are compared to the threshold curve measured on the fingertip by Verrillo, but, as acknowledged by the authors themselves, the threshold used was not fully appropriate in this study.

Indeed, apart from the fact that the skin sensitivity to vibratory stimuli is critically dependent on the vibration frequency, several other physical parameters have been shown to influence the sensitivity to tactile stimulation: location, contacting area, pressure, in particular. These factors may (all) be considered in the case of violin holding and playing. The location on the body has been found to be one of the major factors that provide differences in skin sensitivity. In particular, the fingertips and facial regions were reported to have the lowest thresholds for vibration detection of the human body [14, 15, 16]. In the case of violin holding, it is the base of the index and the first phalanx of the thumb that are usually in continuous contact with the violin neck. The vibration sensation threshold also appears to vary as a function of the contacting area such that larger contactors produce lower thresholds [17]. The fingertip corresponding to a contacting area as small as 28 mm^2, the threshold used was most certainly an underestimate of that in the case of violin holding which involves two areas, for a total of approximately 5 cm^2. Finally, differential sensitivity has been found to be dependent on the pressure of the skin on the vibrating surface such that increasing the pressure results in lower threshold [18]. In violin playing, a small pressure is always applied on the neck [19], whereas the threshold was measured by Verrillo while the fingertip was slightly touching the vibrating contactor. Hence, it is of particular interest to take into account the great extent of parameters that can influence the vibration sensation threshold to adapt the threshold curve to the case of violin neck holding.

The present study was designed to explore this phenomenon of vibrotactile feedback existing in the left hand of violinists when playing a violin. The study is principally based on comparisons between vibrational measurements, recorded at the necks of different violins using a standard impulse response procedure, and psychophysical measurements of vibration sensation thresholds made on several violinists' left hands. This investigation aims at characterizing the vibrotactile feedback at necks by determining whether the vibration levels measured at necks are above the vibration sensation threshold of violinists' left hand for all violins under study, and at all frequencies. Furthermore, this paper explores how the vibratory behaviors of violins with respect to the threshold of vibration sensation can be related to the evaluation of a professional violinist regarding the "feel" of the instrument.

This paper is divided into two main parts. In the first part, tactile sensitivity to vibration in the left hand of violinists is examined as a function of frequency in a psychophysical experiment. The second part is dedicated to the characterization of a set of violins. This involves (1) the report of a perceptual evaluation conducted with a professional violinist to collect his feelings regarding the "feel" of each violin of the set, and (2) measurements of vibration levels at violin necks and bridges with a standard impulse response procedure. Vibrational measurements are then discussed with regard to the measured absolute thresholds of vibration sensation.

2. Absolute thresholds of vibration sensation in the left hand of violinists

2.1. Participants

Fourteen skilled violinists took part in this study - eight females and six males - twelve aged between 19 and 36 and two between 50 and 65 (average age = 29 years, SD = 13 years), with a number of years of violin experience ranging from 15 to 56 years (average years of violin training = 23 years, SD = 12 years). Participants were informed prior to the experiment and consented to take part. None of them reported having tactile-related problems. Subjects were paid for their participation.

2.2. Set-up

Absolute thresholds of vibration sensation in violinists' left hand were determined employing a psychophysical method in an experimental situation that mimicked a normal playing situation. The participant violinists were asked to hold an isolated vibrating violin neck (see Figure 1) similarly to how they would hold the neck of a violin when playing an open G, i.e. the left hand holding the neck in first position. The use of a real neck, uncoupled from the body of the instrument, was motivated by the following reasons:

- It prevents the excitation of the violin body by the neck and thus the generation of sound which would interfere with the vibration sensation.
- It guarantees that the violinists feel the vibrations *through the left hand only*.
- It guarantees that the violinists use the *same contact area* as in normal playing.
- It guarantees that the violinists have enough cues to exert the *same pressure* as in normal playing, with the so called muscle memory.

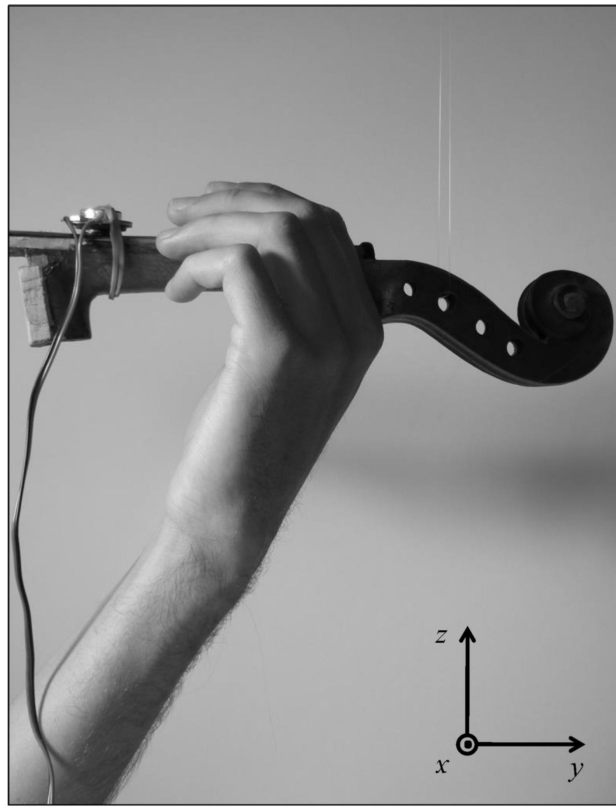

Figure 1. Experimental set up for the vibration sensation threshold measurement: isolated violin neck excited by a small vibrator.

The violin neck was suspended by two very thin nylon strings at both ends. The neck was excited by means of a small vibrator (Dayton Audio DAEX13 Mini Exciter Pair 13 mm) positioned on top of the fingerboard, vibrating in the perpendicular direction of the fingerboard plane (see vertical z-direction on Figure 1). Earmuffs were worn to make high-frequency sounds from the system (vibrator + neck) inaudible.

The thresholds measured here are thus the minimal displacements detectable by the two static and permanent contact areas that typically exist between the violinist hand and the violin neck – a thumb's phalanx and an index' phalanx – in a playing situation. Throughout the rest of the article, these two stationary contact points will be referred to as "violinists' left hand".

2.3. Procedure

Thresholds were determined for seven frequencies included in the skin sensitivity range, from 196 to 900 Hz. The first four frequencies correspond to the frequencies of the four open strings of the violin, namely 196 Hz, 293 Hz, 440 Hz and 659 Hz; the three others are 730 Hz, 800 Hz and 900 Hz to cover the range of the human skin sensitivity. However, the 900 Hz frequency measurements were eventually discarded since the vibrating signal turned out to be too loud not to be interfering with the vibration sen sation. Hence, in the following, we present the results for the six first frequencies only.

Thresholds of vibration sensation were estimated using a three-interval three-alternative forced-choice procedure. On a computer screen, three blocks lit up to inform the subject of the temporal interval in which the vibratory event could occur (the vibratory event was indeed randomly presented in one of the three intervals). The vibratory event was a sinusoidal burst of duration 600 ms with a 30 ms rise/fall time, with a variable amplitude. The interstimulus interval was 1 s. To ensure a permanent pressure on the violin neck, the subject was asked to say orally in which temporal interval – 1, 2 or 3 – the stimulus appeared, and the experimenter typed the answers. Subjects were given trial-by-trial visual feedback of correct/false responses during the experiment. A three-down one-up adaptive tracking rule was used which estimated the 79% correct point on the psychometric function [20]. This rule means that a decrease in vibration level requires three sequential positive re sponses and that a reversal in the track occurs after one negative response. The difference in amplitude between the vibratory stimuli of two successive trials was determined by a predefined factor: the step size. The initial step size was relatively large – $2^{1/2}$ – to ensure a rapid convergence around the threshold. When the first turn-point was reached (i.e. after the first error made by the participant), the step size was reduced to $2^{1/4}$. The procedure automatically stopped after 8 turn-points and the threshold was defined by the mean value of the amplitudes of the vibratory stimuli in the 6 last turn-points. Participants familiarized with the experimental procedure by completing a training run at 440 Hz before beginning the measurements.

2.4. Calibration

The correspondence between the acceleration of the isolated neck at the usual point of contact in first position between the violinist's index and the violin neck and the amplitude of the sinusoidal excitation corresponding to the measured threshold was established after the experiment, for each participant, at each frequency under study. We chose to make the correspondence measurements without hand contact (i.e. to measure the acceleration without the participants' hand on the neck) because the ultimate goal of this threshold measurement is to allow comparison with vibratory levels at violin necks (see section 3.2) which are traditionally measured without the hand, even though the violinist's grip has an effect on the vibration level and spatial pattern of necks [9]. Indeed, in addition to a practical reason (they are easier to measure by a single person), vibratory measurements on violins are usually meant to allow mechanical comparisons between different violins (measured sometimes by different people) or between different stages in the construction of a violin, and thus need preferably to be violinist - independent. Consequently, the threshold curve considered here is an overestimation of the real threshold which would have been obtained by measuring the acceleration while the hand was in contact with the neck.

The two contact areas - thumb's phalanx and index' phalanx - being very close spatially, only one big locus of stimulation is considered in this study. We chose to measure the acceleration at the index locus in first position, where the applied pressure is the strongest [19]. Though the vibrator excited the neck in the vertical direction (see Figure 1), the resulting vibrations at the contact index/neck can occur along all directions. We assumed that at these frequencies – above 50 Hz – humans are not able to determine whether a vibrating stimulus is produced laterally or normally to the touched surface but feel the vibration in a whole. Although to our knowledge there is no behavioral study investigating this hypothesis, there is a physiological basis to support this assumption. In this frequency range [196–900] Hz, the Pacinian receptor population is likely to provide the bulk of the neural signaling [21]. Although the Pacinian receptors are individually selective to the vibration direction, this population is distributed deep within the tissue [22]), such that the effect of the boundary conditions (i.e. the neck holding) can be expected to be negligible.

As a result we quantified the perceived stimulus through the energy of the 3D-recorded acceleration signal, namely the magnitude of the acceleration considered in the three directions: normal to the contact areas on the sides of the neck (x-direction on Figure 1), tangential to the neck (y direction) and normal to the fingerboard (z-direction). The correspondence measurements were made using a 3D accelerometer (Brüel&Kjær triaxial Deltatron®, type 4525-B-001). A double integration of the acceleration magnitude (norm) yielded displacement values in microns which were converted to decibels, with a reference of displacement of 1 micron.

2.5. Results

Figure 2 shows the absolute thresholds of vibration sensation measured at six frequencies on the left hand of violinists (solid line), superimposed with the threshold curve of vibration sensation obtained by Verrillo [13] on the tip of the index (dashed line) for comparison purposes. Our data plotted are based on the medians of the measurements made on the fourteen subjects as a function of the stimulus frequency in Hertz. All reported values represent the minimal displacements detectable by the left hand, in decibels. Thresholds between the last point of measurement (800 Hz) and the end of the skin sensitivity range (100 Hz) are extrapolated.

The general shapes of the functions are essentially the same. In particular, the slopes of the curves (up to 700 Hz) are very similar. Unsurprisingly, the vibration sensation threshold measured on the left hand is slightly lower than the one obtained at the tip of the index (from 3 to 10 dB), most probably because a larger contact area as well as a larger pressure (even if limited) increase sensitivity to vibration detection. The variability of results among subjects is small (about ±4 dB), as shown by the errors bars representing the standard deviation.

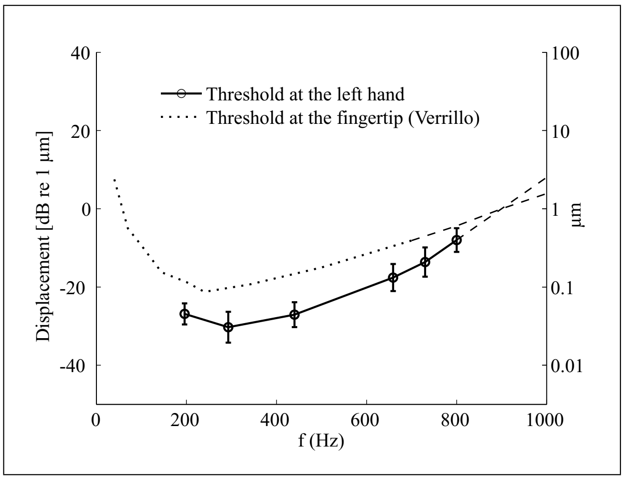

Figure 2. Absolute thresholds of detection for sinusoids measured at the left hand of 14 violinists (solid line) and at the fingertip (dotted line; from Verrillo, [13]). Corresponding micron scale is represented on the right side. Dashed lines represent the extrapolated thresholds. Standard deviations are represented by vertical bars.

The sensitivity slightly increases with frequency from 196 Hz to 293 Hz. At this frequency, the skin of the hand can detect displacements as small as 0.03 µm. The maximal sensitivity of the hand is reached (it indeed corresponds to a minimum of the threshold curve), and it is close to the peak sensitivity of the Pacinian corpuscles at 250 Hz [23]. Above 300 Hz and up to 1000 Hz, sensitivity decreases rapidly until becoming impossible to measure. The most sensitive frequency range for the hand skin is thus within the register of the violin.

3. Perceptual and physical characterization of vibrotactile feedback in a small set of violins

3.1. Perceptual evaluation of a professional violinist

A set of 10 violins was initially assembled in order to explore the possibility of discriminating between them according to their vibrational behavior. The violins were chosen by a luthier for their different playing characteristics (ranging from 800 euros to 6000 euros, and made from early 19th century to early 20th century). A professional violinist was invited to play freely the set of violins for evaluation purposes. He was encouraged to comment out loud about the evaluation process and to report orally his feelings regarding the sound and the "feel" of each violin.

The aim of the study (characterization of violins' vibratory properties from a player's perspective) was not disclosed in order not to orient the violinist's comments towards his vibratory sensations only. The test was conducted in a dark environment and the violinist wore dark sunglasses to prevent detailed visual feedback which could interfere with our research questions. His comments explicitly related to his t actile sensations (i.e. not exclusively oriented towards the left hand) led us to restrict the study to four instruments that were perceived as the most different in terms of vibratory behaviour.

Two of these four violins were described as "vibrating" violins. One of them was perceived as "very pleasant to the touch, it responds very quickly" (« très agréable au toucher, il répond très vite ») with the comment: "by playing a G on the D-string, it makes me vibrate down to the belly" (« en jouant le ré sur la corde de sol ça me fait vibrer jusqu'au ventre »). The other violin "gives a good hand massage" (‹ça fait un bon massage de la main »). On the other hand, the two other violins were described as "non-vibrating" violins. One of them was described as "more inert to the touch" (« il est au toucher plus inerte ») and the other "hard to play, it doesn't respond quickly" (« difficile à jouer, il ne répond pas vite ») with an "inert neck" (« manche inerte »). We decided to focus on these four violins with extreme vibrating behaviours in order to investigate how this perceptual feeling of a "vibrating" violin, regardless of its overall quality, relates to its vibrational behaviour relative to the threshold of vibration sensation presented in section 2.

3.2. Vibrational measurements

Two types of measurements were made:

- Bridge admittance: defined as the ratio of the resulting velocity at a string notch on the bridge over the excitation force applied at the same point, it is supposed to contain essential information about the energy transferred between the string and the body [24]. It is referred to as the classic "acoustical signature" of violin, and it is thus the most common measurement made on violins.
- Vibration levels at the neck in 1st position: As we wanted to investigate the vibrotactile feedback that can be perceived at the violin neck, both horizontal[1] and vertical[2] neck vibrations were calculated from transfer functions bridge-neck, in order to be compared to the vibration sensation threshold measured on the left hand.

The same standard procedure based on impulse response technique was followed for both types of measurement (e.g. [25]). The G-string corner of the bridge was excited with a mini-force hammer (PCB, Model 086E80), in the direction of bowing. The bridge velocity (for the bridge admittance) and the neck velocity (for the horizontal and vertical neck vibrations) were detected by a laser Doppler vibrometer (Polytech, PDV 100) respectively at the E-string corner of the bridge, under the index in first position on the neck, and between D-string and A-string on the fingerboard in first position. The use of a support fixture facilitated the signal acquisition of the laser which requires

[1] Throughout the rest of the article, the horizontal vibrations of violin necks refer to the vibrations measured along the direction perpendicular to the neck axis, in the plane of the violin top plate.

[2] Throughout the rest of the article, the vertical vibrations of violin necks refer to the vibrations measured on the fingerboards along the direction perpendicular to the neck axis and perpendicular to the plane of the violin top plate.

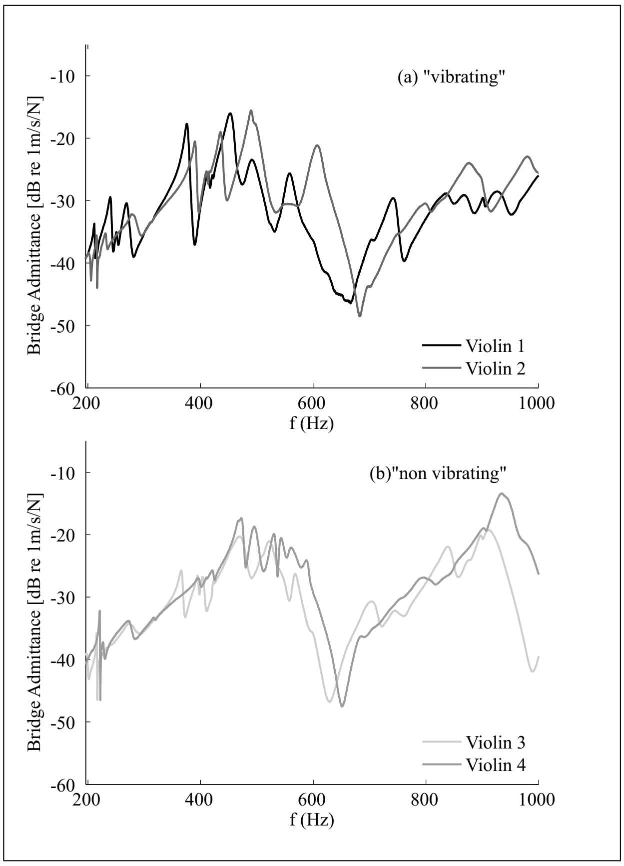

Figure 3. Bridge admittances of the four violins selected according to their perceived vibratory behaviour: (a) “vibrating” violins (b) “non-vibrating” violins. Levels are plotted in dB re 1 m/s/N.

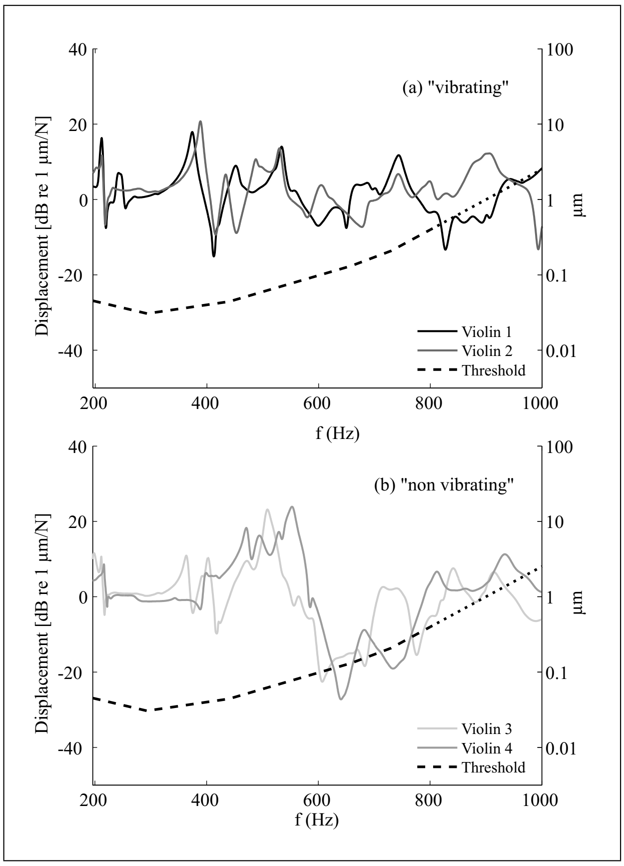

Figure 4. Horizontal vibration levels at the side of the necks of violins perceived as (a) “vibrating” violins (b) “non-vibrating” violins. The measured threshold of vibration detection is reported on the graphs (dashed line).

the structure to remain completely still: the instrument was held clamped on a rigid board with the chinrest removed and replaced by a fixture. The strings were tuned to pitch and damped with a small card on the fingerboard.

The transfer functions bridge-neck were converted into displacements in two steps. An integration of the velocity yielded displacement values in microns which were converted to decibels, with a reference of 1 micron displacement. Second, the excitation force was chosen equal to 1 N as it corresponds to classic playing dynamics (between mezzo forte and forte). Indeed, the excitation force of the hammer blow on the G-string corner of the bridge can be traced roughly to the excitation force F at the bridge by the string in normal playing with the bow, and hence to the dynamic level, using $F = Z_0 v_B/\beta$ [26], with Z_0, the characteristic impedance of the string considered, v_B the bow velocity, and β the fractional distance from the bridge to the bowing point. The characteristic impedance of the G string is about 0.33 kg/s. A typical bow velocity at mf is 0.2 m/s and the bow-bridge distance is 0.08. That gives the bridge excitation force 0.8 N. Correspo nding values in forte may be roughly 0.4 m/s and β is 0.05, and so F = 2.5 N.

In the following, all measures presented were averaged over two trials. Since the goal of this study is to investigate the vibrational behavior of the violins as perceived by a player, the observation of the curves is limited to the frequency range [196–1000] Hz.

3.3. Results

3.3.1. Bridge admittance

Figure 3 shows the bridge admittances of the four selected violins, both “vibrating” violins (Figure 3a) and both “non-vibrating” violins (Figure 3b) in the skin sensitivity range.

The four displayed curves have the same general shape in the chosen frequency range – the average vibration levels seem to be of relatively equal magnitude among the four violins – although they present local differences. Below 600 Hz, the two “vibrating” violins display, indeed, larger fluctuations in amplitude than the two others. This is in particular due to a large resonance peak for the CBR mode (the lowest frequency corpus mode in which top and back plates move approximately together at each point in a twisting deformation [1]) around 400 Hz for the “vibrating” violins only. In contrast, above 600 Hz, the two “non-vibrating” violins reach a higher amplitude than the other violins. However, bridge admittance curves are delicate to interpret perceptually because, as mentioned in the Introduction, no acoustical/vibrational criteria have been clearly and consistently identified to discriminate between

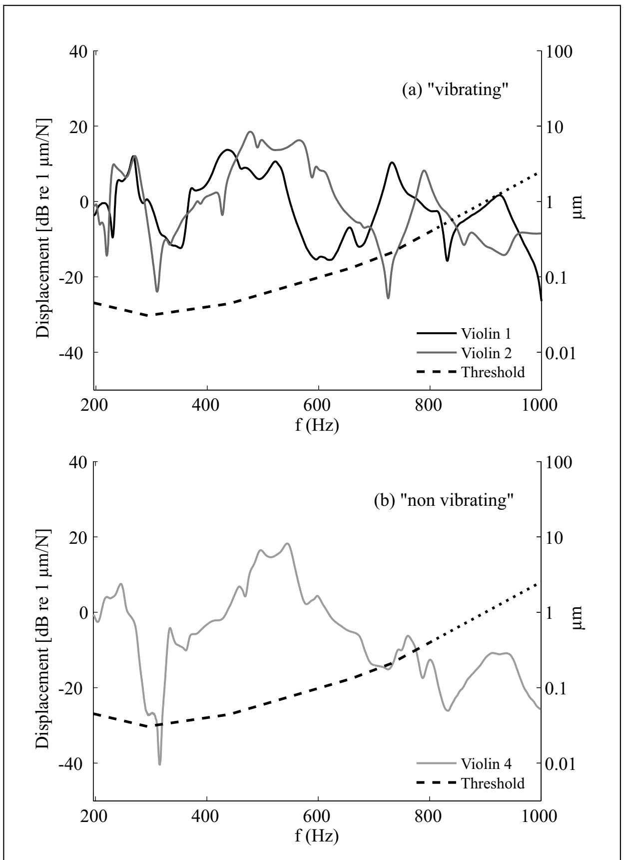

Figure 5. Vertical vibration levels at the fingerboards of violins perceived as (a) "vibrating" violins (b) "non-vibrating" violins. The measured threshold of vibration detection is reported on the graphs (dashed line).

violins. It would thus be premature to determine conclusively what vibrational criterion determines the differences of vibrating character of a violin as perceived by the violinist.

3.3.2. Vibration levels at the neck

The measurements made in the horizontal and vertical directions are presented on two distinct figures to allow comparison with Askenfelt and Jansson's horizontal measurements. Figure 4 shows the horizontal neck vibrations of both "vibrating" violins (Figure 4a) and both "non-vibrating" violins (Figure 4b), measured at the location of the index in the first position, superimposed with our measured sensation threshold.

Similarly to the bridge admittances, the average vibrational amplitudes at the necks of both types of violins are under 600 Hz of relatively equal magnitude and well above the reported threshold. One salient difference is observed above 600 Hz between the two perceptual groups of violins. The horizontal vibrational amplitudes of the necks of "vibrating" violins are well above the measured threshold of vibration sensation (+15 dB in average) up to 800 Hz. In contrast, the curves of the "non-vibrating" violins appear to be less even over the frequency range [200–1000] Hz: the horizontal vibrational amplitudes present an abrupt decrease of about 40 dB around 600 Hz and stay below or just about the threshold.

Due to the unavailability[3] of one of the four violins, the vertical necks vibrations were measured on the fingerboard of only three of the four violins considered in this study. Figure 5 shows the vertical neck vibrations of both "vibrating" violins (Figure 5a) and one of the two "non-vibrating" violins (Figure 5b) superimposed with our measured sensation threshold.

In this direction of vibrations, the difference between the two types of violins is less striking than in the horizontal direction. This does not allow us to draw conclusions regarding the perceived differences between the two types of violins.

The other six violins of the set – violins neither described as explicitly "vibrating" nor explicitly "non-vibrating" violins by the professional violinist – display, overall, intermediate vibratory levels at the sides of the necks relative to the vibration sensation thresholds in the frequency region [600 800] Hz. It is thus more difficult to interpret how their measurable vibratory response would relate to the vibrating "feel" of a violinist. Hence, based on our data, the relative position of the neck horizontal vibration level curves and the vibration sensation threshold may be viewed as a helpful criterion to discriminate between violins with vibratory behaviors perceived as extreme, though further work is needed to confirm the tendencies observed here.

4. Discussion

This paper investigated the phenomenon of vibrotactile feedback that can be perceived through the left hand of violinists in playing, as it was stated to be an important cue to the perception of how a violin "feels". The chosen approach places the physical interaction between the musician and his instrument at the heart of concerns because vibration levels measured at necks are compared with vibration sensation threshold measured at the body region of interest: the violinists' left hand in contact with the violin. This methodology is an attempt to introduce the presence of the musician in the interpretation of vibratory measurements.

As a first step, our investigation focused on four violins, among an initial set of ten instruments, whose vibratory behaviors were perceived as extreme during a perceptual evaluation conducted with a professional violinist (violins explicitly "vibrating" or "non vibrating"); indeed, we considered that extreme characteristics are more likely to highlight subtle effects, perhaps difficult to measure. The psychophysical experiment determining the vibration sensation threshold of the left hand was conducted on violinists holding a real violin neck in order to maximize the validity of the measured interaction. The vibration levels of the violins' necks were measured in both horizontal and vertical directions in the frequency range [196–1000] Hz

[3] Unforeseen sale of violin during the measurement campaign.

since we assumed that in the register of the violin (above 196 Hz) humans are not sensitive to the direction of the vibrations of the object in contact with their hand but feel the vibrating stimulus as a whole.

Although both threshold and vibratory level curves are overestimated compared to when the instrument is held by a player (the thresholds calibration and the physical measurements were made with no hand contact), what is of interest here is the relative position of the two curves.

Finally, as the most classical measurement realized on stringed instruments, bridge admittances were also measured in the frequency range [196–1000] Hz to explore how this perceptual feeling of a "vibrating" violin, regardless of its overall quality, relates to its global vibrational behaviour.

Regarding the bridge admittances, Marshall's hypothesis that the feel of violin – based on vibratory feelings – is "principally determined by the lowest order vibrational modes of the violin" was in part verified in this study. Indeed, the violins presenting the highest resonance peaks below 400 Hz, with in particular a clear resonance of the CBR mode, were precisely those perceived as "vibrating" by the professional violinist who evaluated them, whereas the two others presenting very low reso nance peaks were judged "non vibrating". Violin bridge admittance measurements are nevertheless hard to interpret perceptually because no obvious perceived quality-related trends in signature modes were consistently found in past violin research.

In contrast, with the superimposition of amplitudes of vibration at violins necks relative to the threshold of vibration sensation, an attempt is made to take into account the musician's presence to interpret the physical measurements made on violins.

Results show that the displacement levels recorded on violin necks in the skin sensitivity range, in both horizontal and vertical directions, could significantly vary from one violin to another, especially around 600 Hz. In either direction of vibrations, amplitudes of vibration were well above the threshold of sensation at all frequencies under 800 Hz for both violins that were described as "vibrating" violins, whereas the relative position of the vibration curves of both "non-vibrating" violins compared with the threshold curve depended on the frequency.

The distinction between both types of instrument was much striking in the horizontal direction, which we consider as the most relevant direction of vibration for this study, where the vibration level curves of the "non vibrating" violins can be split into two clear zones of frequencies (which is not the case of the "vibrating" violins): below 600 Hz where they are well above the threshold and above 600 Hz where they stay below or close to the thres hold, with a very abrupt level decrease in-between, of approximately 40 dB. This could be described as a cutoff frequency at about 600 Hz.

With this in mind, Marshall's second hypothesis [9] could thus be reformulated. Rather than saying that the vibrating character of a violin would depend on the number of times a violin neck resonance level is above the vibration sensation threshold, one could say that the relative position of the vibration level curve of violin necks compared with the threshold of vibration sensation reflects the vibrating character of a violin.

It is likely that violinists are particularly sensitive to the abrupt level changes while playing over the register of the violin included in the vibrotactile domain. O'Modhrain's [7] claim that "only when the response of the instrument changes suddenly is the player again conscious of its "feel" (Chap.5, p.72) could explain why an abrupt decrease in the level curve alone can account for the differences perceived between the two types of violins. With our results, the more even it is over the playing range of the violin, the more "vibrating" the violin is perceived.

Furthermore, it is interesting to note that the rapid drop around 600 Hz observed on the curves of "non vibrating" violins is in fact a distinct feature of violins that classically appear in the bridge admittance measurements (and which is clearly present for all four violi ns), and which is due to the absence of vibrational modes in the region [600–700] Hz.

An interesting question is now to explore why such a drop was not observed in the neck vibrations of "vibrating violins", since neck vibrations are directly related to all the vibrational modes of the instrument measured at the bridge. The differences of body/neck or neck/scroll coupling could explain this difference in vibratory response, for which admittances measured at the nut could be useful, but it is beyond the scope of this study. Incidentally, it might be noted as well that mechanical and perceptual differences between the two categories of violins cannot be explained by the price of the instruments.

5. Conclusion

This investigation provided quantitative and perceptual support for the observation of Askenfelt and Jansson [12] that violin necks vibrations can be felt by players while performing. However, by placing greater emphasis on the playing context (threshold measured using a real violin neck, and levels of vibration at the neck corresponding to classic playing dynamics interpreted relative to the threshold), our experimental procedure allows to extend their findings, and modulate them in line with the violin and the notes played on it.

Indeed, our results mean that for notes higher than D5 (587 Hz), the vibrations can be sensed for "vibrating" violins but hardly for "non-vibrating" violins. For notes lower than D5, the vibrations can be sensed in both types of violins but the intensity of the perceived vibration should be different considering that the amplitude of the lowest partials of each note played can change the strength of the vibration felt. The fundamental vibration for notes lower than D4 was indeed of relatively equal magnitude for both types of violins but the partials in the range [600 Hz–1000 Hz] will be perceived for the "vibrating" violins only.

A related question is thus the influence of the string vibrations acting on the finger when playing non open strings, which might also have an effect on the sensation of vibration. It would be interesting to take them into account in future investigations.

This methodological-oriented study is thus a preliminary descriptive stage to provide some evidence of the existence of violin-dependent tactile feedback in the left hand of violinist. This feedback could be viewed as a potential perceived signature of the violin played. Further work is necessary to confirm this trend with a larger panel of violins and a greater number of violinists who would evaluate the instruments according to their "feel" and to common attributes of violin playing. Ultimately, future studies are needed to investigate how violinists make use of this vibrotactile feedback while playing and whether the perceived vibrations play a role in the evaluation of the quality of a violin.

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