Feature-Based Analysis of the Impact of Ground Coat and Varnish on Violin Tone Qualities

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Summary
Assessing the tonal qualities of an acoustic musical instrument is a challenge that has long been pursued by researchers in musical acoustics. This is a topic of particular interest when it comes to discussing the case of violins. Historical violins are often believed to owe a great deal of their celebrated timbral qualities to the choice and the make of their finishings, particularly the ground coat and the varnish. The impact of such finishings on the instrument's tonal qualities, however, is not so well understood. In this paper we investigate the impact of the finishing process on the instrument's timbre through a joint analysis of the characteristics of the materials involved for this process (ground coat and varnish) and audio features extracted from the sound produced by such violins at various stages of their finishing. Some of the results are compared with those found in the literature for validation purposes. The characterization of the impact of ground coat and varnish has been conducted during the finishing process of a new violin.

1. Introduction

The violin occupies a special place in the history of musical instruments. Although its ancestors date back to the early renaissance period, for centuries its shape and structure have remained practically unchanged. Its name comes from the Italian word *violino* (*small viola*), and is probably derived from the Medieval Latin word *vitula*, which means "stringed instrument". The first modern violins were built in the early sixteenth century, about the time when the viola and the cello made their first appearance as well. The acoustic qualities of acoustic musical instruments, especially violins, depend on all aspects of the construction process, from the properties of the wood, to the geometries of the parts, all the way to the finishings. In particular, they are heavily dependent on the chemical characteristics of the materials used by the violin maker, as well as their interactions with the wood.

The finishing process turns the untreated instrument (bare wood) to a ready-to-play one. It includes two main steps. First, a "ground coat" on the untreated violin is applied, with the purpose of filling the pores of the wood, thus preventing the wood from absorbing the varnish. Many natural substances are traditionally used (siccative oils, gums, hide glue, bone glue, rabbit glue, egg white, casein, etc) and, among them, proteinaceous substances such as casein, which are still the most widely used. The second step consists of the application of several layers of varnish, with a twofold purpose: (i) protecting the wood from dirt, sweat and biological degradation of the wood [1], (ii) covering the instrument with a colored coating, which has a purely aesthetic function. The varnishes used for stringed instruments can be divided in three main categories: essential oil varnishes, oil varnishes and spirit varnishes. [2]. These varnishes sometimes contain substances of vegetable (e.g. dammar resin, elemi gum, siccative linseed oil) and/or animal (e.g. shellac) origin. There are thousands of historical recipes for the preparation of varnishes for surfaces finishing, and a few hundreds of them are found suitable for musical instruments[1].

The fact that a violin exhibits different layers of non-homogeneous material [3, 4], such as wood, filler, varnish and so on, makes the study of the correlation between material and tone quality quite complex [5]. A question that researchers and scholars often ask is: how can the finishing (which amounts to a very thin layer of material) affect the timbre of this instrument so much?

[1] VERNIX: Une base de données de recettes de vernis issues de sources écrites anciennes - http://vernix.citedelamusique.fr.

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In order to study the impact of finishings on the tonal qualities of the violin it is important to analyse some aspects of the timbral characteristics of the instrument at every relevant step of the finishing process. In this contribution we analyse the violin and its tone in three different moments of its construction: before the application of ground coat and varnish; after the application of the ground coat; and after the varnish has been applied and is completely dry. At each one of these steps, we analysed the material as well as some features related to the timbre of the violin. These analyses have been conducted on a violin that has been constructed for this specific purpose by an expert violin maker, and all steps are described in detail.

As far as the analysis of materials is concerned, in order to study the physical interaction between ground coat and varnish; measure the penetration depth into the wood; and measure the thickness of the varnish layer, a qualitative and a quantitative analysis using optical (OP) and electronic (SEM-EDX) microscopes were conducted.

As for the sound analysis, we analyzed the timbre of the violin in its different finishing steps, by recording, with the help of a professional musician, a set of notes, musical scales and excerpts of song. Recordings have been accomplished in a semi-anechoic room with controlled environmental conditions. From the recorded sound we extracted a set of descriptors that characterize the different aspects of the timbre [6, 7]. In particular, we enriched the set of descriptors introduced in [8].

Our analysis proceeds through the measurement of the variation of the descriptors along the various finishing steps. In order to select the descriptors whose variation is actually determined by the finishing, we also computed the variation of the descriptors from recordings of a reference violin played by five musicians. Only the descriptors that exhibit a relevant variation in the violin under study and small variations for the reference one are used in our work. Some interesting conclusions can be drawn from this analysis. The ground coat covers the material with a compact layer of about 20μm. Despite its limited thickness, it has a significant impact on the timbre, as it reduces the overall emitted acoustic energy, and emphasizes the spectral peaks at high frequency. The application of the varnish, on the other hand, is more limited and it only partially attenuates the modifications brought by the ground coat. In order to further motivate our study, we also measured the vibrometric frequency response of a soundboard before and after the application of the ground coat.

The rest of the manuscript is structured as follows: Section 2 offers an overview of the state of the art. In section 3, we illustrate the material analysis and the main results. We then discuss in 4 the impact of the ground coat on the vibroacoustic behavior of a soundboard. In section 5.2 we offer a spectral analysis of the recordings of the violin at different stages of the finishing. This motivates the feature-based analysis illustrated in 5.3, whose main results are presented in 6. Finally, in Section 7 we draw some conclusions.

2. State of the art

The violin has been a subject of research for decades, due to its complex behaviour, which is the result of the interaction of many parts and is affected even by the smallest changes. Several aspects have been considered by scientists: the vibroacoustic behaviour, the properties of the woods that are traditionally used, the composition of the varnishes and their interaction with the wood, and finally the relation between materials and sound quality. In this section we provide a short overview on each of the above research areas.

2.1. Violin physics and acoustics

In [9], Woodhouse presents a review on the acoustics of string instruments. The review includes the non-linear vibration of the strings, the response of the instrument's body and the sound radiation. Furthermore, it also touches perceptual studies on the playability of the instrument. Another overview of the physics of bowed instruments is provided in the book by Rossing [10], where the mechanical interactions, the frequency response and the modes of vibrations are explained in depth. The interaction between bow and strings is illustrated also in [11], while the vibration of the body is discussed in [12].

The bridge-hill [13] [14] was recently suggested as a major physical measure for evaluating the quality of a violin. In this regard, in [15] the author evaluates three violins of professional quality and one soloist's instrument made by Guadagnini in 1778. Four notes were recorded for each violin: the open string G (196 Hz), the fifth note A4# (466 Hz), the 12th note A5# (932 Hz), and the G6 (1568 Hz). In order to get a subjective judgment on the timbre quality, the notes were played back and filtered by an equalizer in octave subbands. Each band was isolated and classified by the author according to the magnitude of influence on the overall timbre. The results highlighted that for each note played, the band which has the strongest influence on listening is the one that includes the bridge-hill prominence ($\sim$ 2.5 kHz).

2.2. Materials and their relations with sound

There are several studies that concern violin varnishes, in particular for old Italian violins. Indeed, researchers showed a great interest towards both the preparation of the varnish and the effect on the instrument's behaviour. In [16] and [17], the author presents a survey on the studies on Cremonese varnishes, taking into account both the inorganic and organic composition and the coloring. He highlights how the scientific analysis revealed that the Cremonese finishes are much more complex than traditionally assumed and characterized by many ingredients, so that different results could be obtained by modifying the recipe. In [2], Optical Coherence Tomography (OCT) is applied to an old Italian violin in order to examine the 3D structural elements of the varnished wood. This study shows the efficiency of OCT and the possibility of using OCT to image varnish coatings on wood, in terms of morphological properties and compositional properties. In 2010, Brandmair and Greiner published an in-depth study on the finishing process performed on several Stradivari violins [18], using non-damaging methods such as visible spectrum, UV light, infrared and X-ray spectroscopy, histochemical staining and solubility. SEM (Scanning Electron Microscope) and EDX (Energy-Dispersed X-ray spectroscopy) are used in [19] in order to analyse varnishes from ancient Cremonese violins (Guarnieri, Ruggeri, Stradivari). They revealed the presence of crystals both in the varnish and in the ground-coat layers. Calcite, quartz, potassium feldspar, gypsum and hematite were identified as the main components in the samples under study. According to the authors, these findings cannot be explained as accidental, and the role of these varnishes is more than decorative.

The interest in varnishes is motivated by the fact that they have a great impact on the final tone (as well as other manufacturing materials), and an investigation is in order as remarked in [17]. Some of the above studies, indeed, focus on the interaction between the finishing operation and the acoustic response [20], [21], [22]. As far as the impact of the ground coat is concerned, a summary of some studies is presented in [23] along with a new study on different types of substances, but no particular attention is paid to casein-based materials, which is widely used by violin-makers. This motivates us in investigating on the impact of casein-based ground coat on the response of the instrument. Minato [20] showed that the Acoustic Converting Efficiency (ACE) falls down drastically just after varnishing, but it recovers for 1 year. Furthermore, the change of Young's modulus (E_R) becomes almost undetectable within several months, whereas the decrease of the loss factor continues for a longer period. Schelleng [22] conducted dynamic measurements of the Young's modulus on spruce wood with different types of varnish and measured the acoustical effects in terms of mass, stiffness, and internal friction. He pointed out how the varnish layer causes a loss in terms of emission and resonance, concluding that the varnish layer should be thin and that some final adjustments to the plates thickness should be done after varnishing. In the second half of the 20th century, Meinel [21] studied the correlation between such response curves and the type of wood, as well as the correlation with the type of varnish.The author drew some conclusions on the perception of sound quality, by pointing out a number of frequency bands of interest. Meinel's observations were not able to confirm that the varnish could offer any relevant contribution to acoustic indicators of quality. In [24] Ono conducted a study based on Schelleng's and Meinel's works in order to investigate the properties of the wood before and after the finishing in terms of Young's modulus and internal friction (Q_R^{-1}). This work was also unable to conclude whether the finishing had any beneficial impact on the instrument's acoustics, but some interesting conclusions were drawn. The authors noticed that the application of the varnish would cause the response at low-frequencies (<300Hz) to be diminished, whereas the measured energy at high-frequencies (>3 kHz) would vary depending on the values of E_R and Q_R^{-1} of the wood. Using wood of low E_R, the frequencies above 300Hz would be enhanced due to a relevant growth of E_R after the application of the varnish. Conversely, using wood of high E_R, the frequencies above 300Hz would be attenuated due to a more relevant growth of Q_R^{-1}. This led to the conclusion that the frequency characteristics of the soundboards can, in fact, be controlled to some degree by the finishing process.

Broadening our focus to the relation between wood and sound, several studies have been conducted, like [25], [26], [27]. In [25], some parts of a violin have been subjected to a chemical treatment. It is shown how some properties (like the internal friction and the Young's modulus) change, improving the violin tone from a perceptual point of view. In [26], the effects of aging on the vibrational properties of wood are studied. It is shown that the aged wood exhibits higher sound velocity and lower mechanical loss tangent than the new wood. The ratio of Young's modulus and shear modulus (EL/GL) remained unchanged or increased slightly during the aging period. In [27], the authors studied if it is possible to treat the wood in order to make it acoustically similar to the wood used by Stradivari, which was characterized by high modulus of elasticity and low density. They show how it is possible to achieve a density reduction and an improvement of the radiation ratio [28] by incubating wood specimens with suitable fungal species.

2.3. Feature-based timbral analysis

Feature-based methodologies are widely considered as particularly effective for the analysis of the violin tone [29]. The first studies based on audio feature extraction and analysis aimed at investigating sound quality perception began to appear over two decades ago. In [30] Łukasik et al. analyzed the dissimilarity factors of the timbre of various master violins, i.e. the features that enable to automatically distinguish between instruments. Two methods for the feature ex-

Figure 1: The violin in the three steps of the making process. Untreated (left), with ground coat (center) and varnished (right).

traction process have been applied: one based on the harmonic spectral parameters (brightness, relative energy of odd and even harmonics, three tristimulus coefficients) and one based on the auditory model of the human ear. The original set of features was very large, therefore a feature reduction stage was introduced in the analysis chain.

Timbral analysis that relies on feature-based representations is also applied to musical instrument identification. In [31, 32] the authors used a set of multiscale Mel-Frquency Cepstral Coefficients to the pairwise discrimination of musical instruments. As far as bowed instruments are concerned, in [33] the author used Long Term Cepstral Coefficients to characterize the subtleties of violin sound.

In [34] the author extracted several harmonic features from a collection of 53 violin recordings. A set of linguistic descriptors of the violin timbre was related to these features. The result of the analysis was the allocation of the recorded violins in several semantic categories. This study also showed that the four strings exhibit different values for the same feature. Therefore, each string was evaluated separately.

A semantic description of the violin timbre was also provided in [35] and [36], where a set of bipolar descriptors from natural language are modeled by means of large sets of acoustic cues extracted by 28 historical and modern violins.

3. Material analysis

In this Section we motivate the analysis of the impact of the varnish and the ground coat by showing the modification induced to the instrument by the application of ground coat and varnish layers .

3.1. Finishing procedure

For our study, we took advantage of the collaboration with an expert violin maker, who built a violin purposely for our studies.

In order to analyse the materials used in the violin making process and their interaction, we had to acquire a sample. We could not get one directly from the violin without compromising or affecting the acoustic properties of the musical instrument. This is why two wooden boards were taken from the same pieces of wood used for the top (spruce *Picea abies* from Val di Fiemme, Trento, Italy) and back plate (maple *Acer pseudoplatanus* from the Balkans) of the violin, respectively. These boards were cut along the same radial-longitudinal direction of the top and the back plates of the violin. The specimens, free from visible defects or knots, were cut for a length of 14 cm along the direction of the wood fibers; 11 cm along the radial direction of the annual rings; and with a thickness of 4 mm. All the treatments that the maker applied on the top plate and the back plate of the violin, i.e. the ground coat application and the varnishing, were exactly replicated on one side of the sample boards. Each layer of material was laid upon the previous one in a subsequent portion of the board, the last portion of which ended up including the whole stratigraphy. Each treatment was done simultaneously on the violin and on the specimens, in order to match the environmental conditions. The various treatments along with a representation of the corresponding stratigraphy, are shown in Fig. 2.

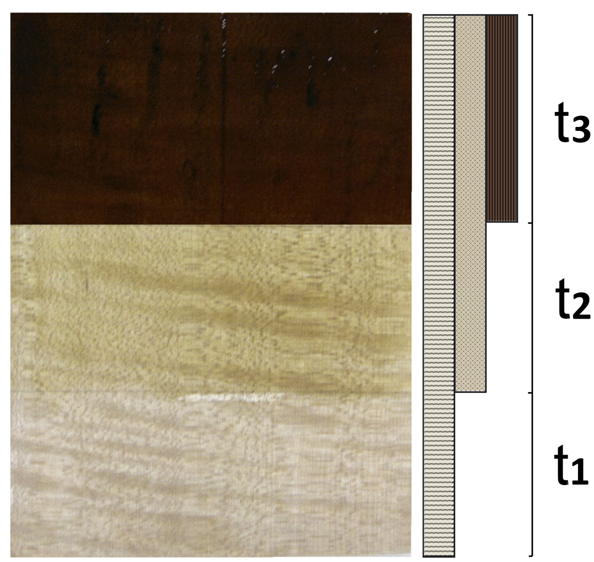

Figure 2: The various treatments applied to the maple sample board (left) and a representation of the corresponding stratigraphy (right): untreated (t1), with ground coat (t2) and with varnish (t3).

3.2. Analysis methodology

In this study the sampling was realized on the two boards in correspondence of the untreated wood (t1), with ground coat (t2) and with varnish (t3). The preparation of the ground coat (t2) begins with the casein, composed of different proteinaceous organic molecules , which are made soluble by adding to it a basic (pH>7) substance (e.g. lime, i.e. $Ca(OH)_2$), thus resulting in calcium caseinate in an aqueous solution. The varnish (t3) is composed of several resins (i.e. mastic, turpentine, shellac, benzoe, elemi) dissolved in alcohol (therefore called spirit varnish), added with various raw pigments and colorants. As mentioned above, the portion on which the last treatment was performed includes all of the underlying layers. A preliminary evaluation of the samples (5x5x4mm in size) was carried out with an Olympus SZ61 stereoscopic microscope equipped with a LEICA CLS 50x illuminator in visible light. The samples were then embedded in epoxy resin and cut using a diamond blade. The resulting cross sections, were first abraded with carbon papers (600-4000 mesh) and then polished with diamond pastes of decreasing grain size (6, 3, 1, 0.25 μm). We looked at such samples using an Olympus BX51TF polarized light microscope equipped with an Olympus TH4-200 lamp (visible light) and an Olympus U-RFL-T (UV radiation). This allowed us to study both the morphology and the stratigraphy of the samples, inspecting the interaction among different layers and the thickness of each one. The cross sections were then coated with a gold film, using a Cressington 208HR sputter coater, in order to make the surface conductive. Higher magnification observations (backscattered electron - BSE - images) and microchemical analyses (energy-dispersive X-ray spectra) were thus performed using a Tescan Mira 3XMU-series FESEM equipped with an EDAX spectrometer. The penetration of calcium as a casein marker was then measured through a semi-quantitative analysis performed transversely through the section. The operating conditions were as follows: accelerating voltage 20 kV, counts of 100 s per analysis, and working distance 15 mm. The semi-quantitative data were obtained by processing the experimental results with the EDAX Genesis software.

3.3. Results

As the results of the material analysis were found to be nearly identical for both wood species, only spruce samples are here shown. As it can be noticed in Figure 3, where early wood is displayed, optical microscopy observations of the spruce wood layer show a very homogeneous structure that primarily consists of longitudinal tracheids and/or fiber tracheids (tr), generally with uniseriate bordered pits. In addition to the vessel cells, thin medullary rays (mr) and a resin canal (rc) can be distinguished. The microscopic images collected in visible (Figure 3a) and ultraviolet (Figure 3b) light, which is characteristic of the spruce sample treated with filler and varnish (t3), clearly show the presence of the varnish layer, uniformly distributed on the wood substrate. This upper layer, which does not penetrate wood cells, appears in a dark brown hue under visible radiation, and in an orange-color hue under ultraviolet light. As predicted, no evidence of calcium caseinate between varnish and wood can be found. Notice that the wood is not excited by the ultraviolet radiation and the blue-violet visible component (as spurious) of the source is entirely reflected. In order to check whether the casein layer (t2) could be recognized at higher magnification levels, electronic microscopy observations were carried out. The brightnesses/darknesses of SEM-BSE images are correlated to the atomic number of the elements within the sampling volume. In particular, the greater the atomic number, the greater the brightness, which provides us with useful information about the distribution of different elements in the sample. However, the atomic number of the calcium caseinate elements is similar to that of the wood. This means that the gossamer casein stratum could not be easily distinguished inside wood (Fig. 4) merely through qualitative observations. However, the higher concentration of calcium in the calcium caseinate with respect to the wood turns it into an elemental marker that allows us to characterize its penetration inside the wood. This is why we performed a semi-quantitative line profiling analysis of calcium concentration transversely through the section. We measured the concentration every 1 μm along the line, both in the untreated (t1) and treated (t2) sample. As we can see in Fig. 5, the concentration of calcium as a marker of the calcium caseinate decreases to its minimum at around 30 μm depth inside the wood, where it reaches the concentration values similar to that of the untreated wood. This means that the casein does not create a layer upon the support but it soaks in the wood producing a shell with an average thickness of 30 μm. We also measured the wood thickness of both untreated top and back plates through a violin thickness gauge. At the center of the top and back plates and along the ribs, where the arching are less marked, the calcium caseinate treatment affects

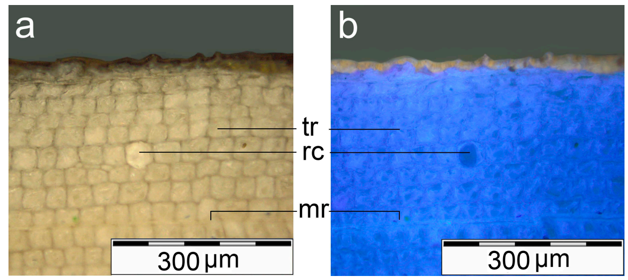

Figure 3: Optical microscopy images (20X) of the cross section after applying ground coat and varnish (t3): visible light (a) and UV induced fluorescence (b). Anatomical wooden structures: medullary ray (mr), resin canal (rc), tracheid and/or fiber tracheid (tr)

the thickness by 1.00%, 1.86%, and 2.00%, respectively. This variation is caused by the difference in thickness of these parts.

Due to the presence of casein, the varnish does not penetrate the support: this allowed us to measure the average thickness of the layer, which is about 40 μm. Being a superficial coating, this affects the total thickness with percentages that depend on the thickness of the top and back plates. We compared the thicknesses of finishing layers and untreated wood, shown in Fig. 6 through a color map. As the ribs have constant thickness of 1.05 mm, the varnish coating accounts for a constant 2.6% of the total thickness. It is interesting to notice that the finishing has a greater impact in proximity of the bellies of both top and back plates.

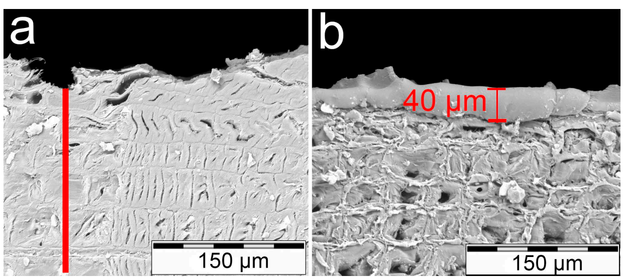

Figure 4: Electronic microscopy BSE image (1000X) of the cross section after applying ground coat (t2): the red line represents the semi-quantitative analysis (EDX) trajectory performed transversely through the section (a); electronic microscopy BSE image (1000X) of the cross section after applying ground coat and varnish (t3): thickness measure of varnish stratum (b)

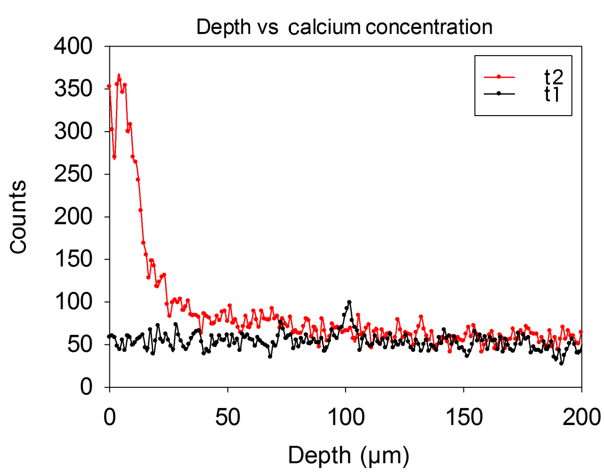

Figure 5: Penetration depth (μm) of Calcium: the concentration measured through semi-quantitative analysis (EDX) along the red line of Fig.4a decreases to its minimum around 30 μm of depth

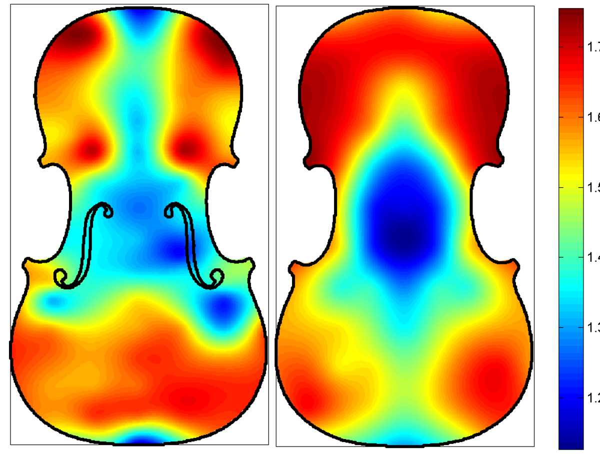

Figure 6: Total thickness variation (percentage) of the top (left) and back plate (right)

4. Impact of the finishing on the vibrational properties

We conducted a measurement of the vibroacoustic impulse response of a soundboard before and after the application of the ground coat. The soundboard was suspended with nylon cables. Three piezoelectric uniaxial accelerometers (mass 0.5 g, sensitivity 1 $mV/(m/s^2)$, range 9000 m/s^2, bandwidth 10 kHz) were placed on the soundboard, which was excited using a small impact hammer (mass 5 g, sensitivity 22.5 mV/N) over 7 different points. Thus, we obtained 21 combinations of excitation and measurement points. For each combination we obtained the Frequency Response Function (FRF) as the average complex ratio between the measured acceleration and the input force. In order to reduce the impact of noise and external factors in the measurement process, for each excitation and measurement point five hits have been averaged.

The frequency responses are shown in figures 7 and 8 for the low and high frequencies, respectively. Frequency responses have been normalized so that the first peak is equal for the two responses. It is interesting to notice that low frequencies are almost unchanged, while high frequencies exhibit a relevant magnification of the resonance peaks in the $t2$ step. The next sections will analyze the impact of this fact on the acoustic and timbre of the instrument.

5. Timbral Analysis

In this section we first introduce the data acquisition procedure. We then illustrate some preliminary results based on the analysis of the average spectrum of some recordings on the instrument under analysis. Finally, we provide an overview of the timbral features adopted in this study and we describe the feature extraction procedure.

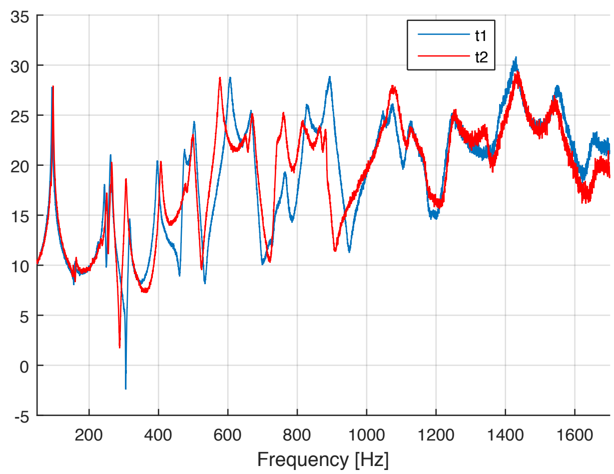

Figure 7: FRF (from 100 to 1700 Hz) measured on a soundboard before and after the application of the ground-coat

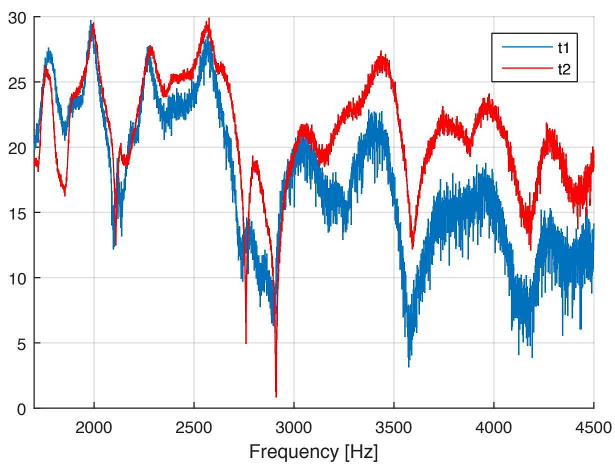

Figure 8: FRF (from 1700 to 4300 Hz) measured on a soundboard before and after the application of the ground-coat

5.1. Audio data acquisition and data preparation

In order to minimize the influence of the environment, we performed recordings in a semi-anechoic room within the *Museo del Violino* in Cremona, Italy. The room has a size of 6x4x2.8m and a reverberation time $T_{60} = 100$ms. A silent air-conditioning system is installed, which controls temperature and humidity, set to 21°C and in the range of 45%-55%, respectively. Before each recording, the violin was left in the room for a few hours to adapt the local climatic conditions.

The instrument involved in the finishing was always played by the same professional musician. For each recording session, the musician was asked to play a sequence of notes (see Table I), selected in order to excite as many frequencies as possible by moving along the entire neck.

String	1st	5th	10th
G	G3 (196 Hz)	D4 (293.7 Hz)	B4 (493.9 Hz)
D	D4 (293.7 Hz)	A4 (440 Hz)	F5# (740 Hz)
A	A4 (440 Hz)	E5 (659.3 Hz)	C6# (1109 Hz)
E	E5 (659.3 Hz)	B5 (987.8 Hz)	G6# (1661 Hz)

Table I: Full list of single notes played. The notes are represented by the name comprehensive of the octave number combined with the related pitch frequency in parenthesis.

The notes were played at nearly constant intensity, with the bow moving slowly both upward and downward, every time waiting for the sound to completely die out before moving on to the next note. In order to reduce the impact of possible noises, interfering signals, and performance-dependent features, each note was played moving the bow three times upward and three times downward, resulting in six recordings per note. In addition, in order to emphasize as many timbral characteristics as possible, a more expressive performance was done by executing a major scale and two excerpts of classical musical compositions 50 s long:

- an excerpt of J.S. Bach's Allemande, from the Violin Partita No.2 in D minor, BWV 1004, with notes ranging from C4 (261 Hz) to B5 (987 Hz).
- an excerpt from W.A. Mozart's Violin Concerto No.5 in A major, K 219, with notes ranging from A4 (440 Hz) to E6 (1318 Hz).

A summary of musical performances is given in Table II.

Strings Involved	Notes	Labels
G	open string	G
	fifth note	GV
	tenth note	GX
D	open string	D
	fifth note	DV
	tenth note	DX
A	open string	A
	fifth note	AV
	tenth note	AX
E	open string	E
	fifth note	EV
	tenth note	EX
G - D - A - E	major scale	sc
G - D - A - E	song 1	s1
G - D - A - E	song 2	s2

Table II: List of the musical performances recorded for each step. For each performance is indicated which strings are involved and which notes were played. The labels associated to the musical performances that will be used in the rest of this work.

The application of the ground coat and the varnish requires the removal of the strings and the bridge (therefore also of the soundpost). For this reason, in order to obtain results that are as comparable as possible, before each recording session, the violin maker accomplished a re-setting of the instrument.

We performed the recordings using a pair of Beyerdynamic MM1 omnidirectional measurement microphones placed in the proximity of the bridge and of the neck of the instrument. The sound was recorded with a high-end recording system, composed of an Aphex 188 preamplifier[2] and an Apogee Symphony A/D converter[3] working at a sampling frequency of 48kHz. A preprocessing phase was included, aiming at removing the silence frames.

5.2. Spectral analysis of audio recordings

In this analysis we show the spectral behaviour of the violin at different finishing stages. In particular, we computed an average spectrum of the recordings from scale and excerpts using the method proposed in [37] and [38]. As we performed the analysis on the audio recordings, we expect the spectrum to also include peaks that are related to the fundamental frequencies and the harmonics of the played notes. These frequencies were discarded in our analysis since they were not relevant for our purposes.

Table III shows the identified modes in the range 200-800 Hz (no resonances could be identified beyond this range). This region includes the Corpus modes, that are the ones most related to a wide motion of the violin belly. It can be noticed that the finishing steps did not produce large variation of these modes. As the vibrometric analysis on the soundboard showed, there is no apparent impact of the ground-coat application on the low frequency region.

In order to characterize the impact of these modifications of the frequency response to the timbre of the sound, we conducted a feature-based analysis to investigate the impact of these modifications on the perceptual relevant aspects of the sound. This study is illustrated in the next sections.

T1		**T2**		**T3**	
F [Hz]	P [dB]	F [Hz]	P [dB]	F [Hz]	P [dB]
265	32.68	268	33.15	269	30.1
378	31.69	381	28.33	380	27.41
417	36.15	418	36.54		
553	24.84	555	25.79	553	26.34
627	26.23			625	20.88

Table III: Identified resonance modes at each step, both frequency (F) and power (P)

[2] http://www.aphex.com/products/188/

[3] http://www.apogeedigital.com/products/symphony-io

5.3. Feature-based timbral analysis

Analyzing the timbre of an instrument is a tough endeavor, due to the subjectiveness of human perception and the uncertainty on its definition. The timbre perception only partially depends on objective acoustic parameters. Audio features are objective descriptors extracted from the audio signal by means of mathematical procedures. They are the basic components in several sound and music analysis [39, 40, 41, 42, 43] and retrieval [44, 45, 46, 47, 48] applications. In order to provide an effective model able to exhaustively capture these aspects we adopt in this study a large set of audio descriptors (features) introduced in [49, 50, 8] and related to the timbre. According to the captured acoustic characteristics, the audio features that we adopt in this manuscript are categorized as energy features, temporal features and spectral features. The set of descriptors is an extension of the one proposed in [8], which is specifically designed for timbral characterization. The total number of audio features used in this study is 53. The complete list and a brief description of each of them are reported in Table IV. For a more exhaustive mathematical formulation we refer the reader to [49, 51, 52, 53, 54, 55, 8, 56, 57, 58, 59].

We used *Matlab*® for audio data analysis and VAMP plugins [4] for feature extraction. The overall procedure is shown in Fig. 9. We extracted features using a window-based decomposition of the signal. The parameters of the window are: length 2048 samples, hopsize 50%. The feature selection step discards a large percentage of the considered features. However, also the discarded features provided us with valuable information as they qualitatively tell us which timbral aspects are affected by the finishing steps, and how. The feature selection is a commonly adopted procedure within the Information Retrieval community [61], which defined sophisticated techniques for that purpose. All these techniques, however, require a huge amount of data, which are not available for the problem at hand. We resorted, instead, to a simpler approach, detailed in the next section.

6. Results

6.1. Performance selection

For reasons of space, in our analysis features are averaged within each performance. Before any further analysis can be accomplished, we need to select only the performances for which features exhibit a sufficient degree of stability. We do so by computing the variation coefficient of the ith feature within the performance s, defined as the standard deviation $\sigma(i,s)$ divided by the mean $\mu(i,s)$, i.e.

$$\rho(i,s) = \frac{\sigma(i,s)}{\mu(i,s)}. \quad (1)$$

[4] http://www.vamp-plugins.org/

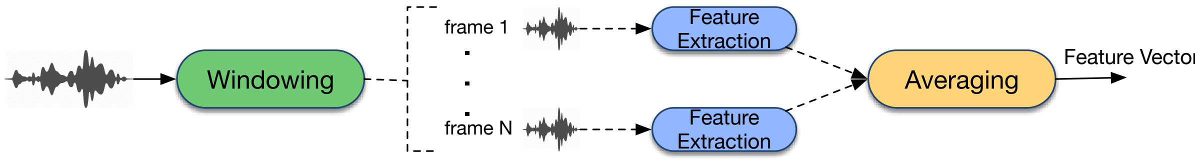

Figure 9: Overall scheme of the feature extraction procedure.

	Feature	Description
Spectral	Spectral Centroid [8, 56]	Geometric center of distribution of the spectrum (first statistical moment)
	Spectral Spread [8]	Standard deviation wrt the centroid of the spectrum (second statistical moment)
	Spectral Skewness [8]	Symmetry wrt the centroid of the spectrum (third statistical moment)
	Spectral Kurtosis [8]	Size of the tails of the spectrum (fourth statistical moment)
	Spectral Slope [8]	Measure of the slope of the spectrum
	Spectral Rolloff [8]	It indicates below which frequency a certain percentage of the total spectral energy is concentrated
	Spectral Average Deviation [8]	Average Deviation of the spectrum
	Spectral Sharpness [57]	Spectral Centroid computed using the specific loudness of the Bark bands
	Spectral Smoothness [58]	Degree of amplitude difference between adjacent partials in the spectrum
	Spectral Crest Measure [8]	Ratio of the maximum value and arithmetical mean of the spectrum
	Spectral Flatness [8]	The tendency of the spectrum to be flat. It is a measure of the noisiness of the sound
	Brightness [55]	Measure of the amount of energy in the spectrum above 1500Hz
	Spectral Entropy [52]	Measure of the noisiness of the sound based on the Shannon entropy index of the spectrum [60]
	Spectral Irregularity J [53] Spectral Irregularity K [59]	Measure of the variations of the successive peaks of the spectrum
	Mel-Frequency Cepstral Coefficients (MFCC) [49]	Compact representation of the spectrum, based on the human auditory model
	Spectral Contrast [51]	Relative distribution of the harmonic and non-harmonic components in the spectrum
Energy	RMS	Typical representation of the signal's energy
Temporal	Zero Crossing Rate (ZCR) [8]	Number of times the audio signal crosses the zero axis. It is a measure of the noisiness of the signal

Table IV: Full list of audio features used in this work. Audio features are divided into three categories, according to the acoustic cues they capture: Energy, Temporal, Spectral.

It is important to notice that the features for which the Variation Coefficient is computed are defined on a ratio scale. It is possible, therefore, to compare the Variation Coefficient of different features. In Table V we show the variation coefficient (only for some representative features and for the step t1, for reasons of space) along with its confidence interval at 95%. First of all it is important to notice that the confidence interval is sufficiently limited, thus motivating us in using the variation coefficient to select the performance. As expected, features that depend on the played note (like the Centroid and the Rolloff) exhibit a larger fluctuation during the execution of the scale and the excerpts. As far as single strings are concerned, the fluctuation is larger on open strings. For what concerns the RMS energy, we do not notice a noticeable difference between the single notes and the excerpts.

As a result of this analysis, in what follows we use single notes for features that depend on the played

	Variation coefficient ± Confidence interval		
Section	RMS	Rolloff	Centroid
G	0.40 ± 0.008	0.13 ± 0.037	0.18 ± 0.030
GV	0.29 ± 0.009	0.12 ± 0.030	0.20 ± 0.010
GX	0.34 ± 0.017	0.08 ± 0.004	0.04 ± 0.008
D	0.53 ± 0.036	0.10 ± 0.010	0.20 ± 0.020
DV	0.29 ± 0.007	0.07 ± 0.024	0.07 ± 0.026
DX	0.30 ± 0.015	0.07 ± 0.011	0.11 ± 0.007
A	0.34 ± 0.014	0.13 ± 0.012	0.11 ± 0.010
AV	0.40 ± 0.014	0.09 ± 0.017	0.20 ± 0.009
AX	0.34 ± 0.023	0.09 ± 0.014	0.18 ± 0.008
E	0.39 ± 0.045	0.12 ± 0.072	0.17 ± 0.045
EV	0.36 ± 0.017	0.06 ± 0.011	0.11 ± 0.006
EX	0.49 ± 0.032	0.07 ± 0.011	0.10 ± 0.008
sc	0.37 ± 0.013	0.29 ± 0.019	0.36 ± 0.010
s1	0.41 ± 0.012	0.21 ± 0.039	0.26 ± 0.028
s2	0.45 ± 0.024	0.18 ± 0.026	0.29 ± 0.012

Table V: Variation coefficient for some of the features that we extracted (at step t1), with the relative confidence interval at 95%

note, and all the performances for feature that do not (like the RMS).

6.2. Feature selection

Another important step that must be accomplished before any further analysis is the selection of the features that are actually impacted by the finishing, and discard those that depend on external factors (musician in first place). In order to accomplish this selection stage, we recorded the same performances in Table II on a reference violin played by $M = 5$ different musicians. More specifically, the reference violin is built using a Stradivarius model similar to the one of the violin under study. We then compare the variation of the low-level features induced by the different players and compare it with the variations on the instrument under analysis. For each feature i we obtained a three-dimensional matrix F by averaging over frames the frame-dependent four dimensional matrix $f_i[m, s, n]$, which depends on the feature i, the musician m, the section s and the frame n:

$$F[i, m, s] = \frac{1}{N} \sum_{n=1}^{N} f_i[m, s, n]. \tag{2}$$

We computed the variation VP for each section s as

$$VP[i, s] = \left| \frac{\max_m F[i, m, s] - \min_m F[i, m, s]}{\mu(i, s)} \right|, \tag{3}$$

where $\mu(i, s)$ is the mean of the feature over the five musicians for section s. Therefore, $VP[i, s]$ represents the variation of the i-th feature in the section s.

We then computed the variations on the instrument under analysis at the different finishing steps, $V1$ for the untreated - ground coat and $V2$ for the ground coat - varnish steps, respectively. For each feature we obtained a three-dimensional matrix $G[i, t, s]$ by averaging over frames the frame-dependent four dimensional matrix $g_i[t, s, n]$, which depends on the feature i, the finishing stage t, the section s and the frame n:

$$G[i, t, s] = \frac{1}{N} \sum_{n=1}^{N} g_i(t, s, n) \,. \tag{4}$$

$V1$ and $V2$ were computed from G as

$$V1[i, s] = \frac{|G[i, 2, s] - G[i, 1, s]|}{\frac{G[i,2,s]+G[i,1,s]}{2}}, \tag{5}$$

$$V2[i, s] = \frac{|G[i, 3, s] - G[i, 2, s]|}{\frac{G[i,3,s]+G[i,2,s]}{2}}. \tag{6}$$

In Figure 10 we compare these variations (averaged over the sections in order to provide a more compact result). We notice that some features exhibit a large variation after the application of the groundcoat ($V1$), while for two of them (Spectral Crest and ZCR) the application of the varnish produces a large variation compared to Vp. We decided to select the features for which at least one of these conditions hold:

$$V1 > 2Vp \,, \tag{7}$$

$$V2 > 2Vp \,. \tag{8}$$

The above constraints allowed us to discard the features that are likely to be not impacted by the finishing procedure. The features that fulfill these constraints are: Spectral Centroid; Brightness; Spectral Rolloff; RMS; Spectral Sharpness; Spectral Crest; ZCR; Spectral Average Deviation. As an additional constraint, we selected only the features that exhibited a confidence interval whose value was small compared to their variation from one step to another. Table VII shows the average value of the features at different finishing steps and their confidence intervals. In particular, this second constraint allowed us to discard Spectral Crest; ZCR; and Spectral Average Deviation. The Spectral Contrast and MFCC variations are shown in separate figures, for clarity. Their variations will be discussed in Section 6.4.

Next sections are devoted to the analysis of the variations of the different categories of features. From this discussion we will be able to draw some conclusions about the impact of the finishing procedure.

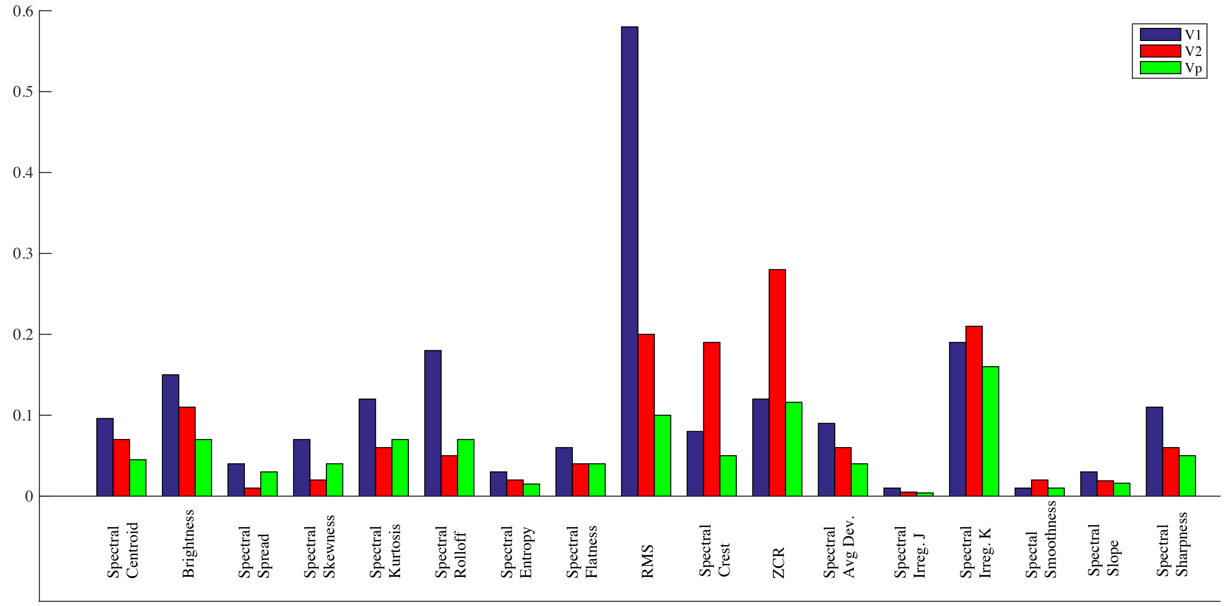

Figure 10: Variation of the LLF in three cases, computed as explained before: from t1 to t2 (V1), from t2 to t3 (V2) and during the execution of the corpus by different musicians with a reference instrument(Vp).

Step	**RMS value ± Confidence Interval**
t1	0.043 ± 0.015
t2	0.023 ± 0.002
t3	0.026 ± 0.002

Table VI: RMS value for each step (averaged over the whole performance), with the relative confidence interval at 95%

Feature	**t1**	**t2**	**t3**
Centroid [Hz]	2252 ± 60	2465 ± 43	2380 ± 31
Rolloff [Hz]	3553 ± 95	4099 ± 110	3939 ± 69
Brightness	0.342 ± 0.012	0.383 ± 0.007	0.373 ± 0.005
Sharpness	0.653 ± 0.015	0.682 ± 0.016	0.692 ± 0.016
Spectral Crest [dB]	104 ± 1.733	102 ± 1.390	108 ± 1.663
ZCR [Hz]	1542 ± 67.288	1531 ± 74.841	1480 ± 69.174
Average Deviation	2554 ± 64.324	2673 ± 75.577	2647 ± 51.320

Table VII: Values of the selected features for each step (averaged on single notes), with the relative confidence interval at 95%

6.3. Discussion

6.3.1. Energy-related features

Table VI shows the RMS values for the three finishing steps along with the confidence interval at 95% of the estimate. Notice, first of all, that the variation between steps $t1$ and $t2$ is two orders of magnitude larger than the confidence interval in both step. As mentioned above, the ground coat and the varnish wrap the instrument with a new layer of materials as identified and quantified by the PLM analysis. Despite their limited thickness, these thin layers can affect the vibrational properties of the wood a great deal. From the RMS analysis we observe that the application of such layers results in an overall damping effect. In particular, as we can see from Table VI, the ground coat is the one that is mainly responsible for the reduction of emitted energy.

6.3.2. Spectral features

In this section we illustrate the results on the selected spectral features that exhibited a large variation (either $V1$ or $V2$). Table VII shows their value along with the confidence interval at 95% of the sample estimate. The Spectral Centroid and Spectral Rolloff are related to the distribution of the energy at different frequencies in the spectrum. As their magnitude increases, the spectrum exhibits a concentration of the energy at high frequencies. This happens with the application of the ground-coat for Centroid and Rolloff. Similar conclusions can be drawn for Brightness and Sharpness, which are based on psychoacoustic curves for their computation. These results confirm that the enhancement of the high frequencies observed in the vibroacoustic analysis has also an acoustic counterpart. We recall that Spectral Crest; ZCR; and Spectral Average Deviation have not been selected as their confidence interval is comparable to their variation from one step to another.

The next paragraph discusses in detail the modification brought to the spectrum at high frequencies through the analysis of MFCC and Spectral Contrast.

Band	Center Frequency [Hz]
1	192
2	496
3	904
4	1452
5	2186
6	3171
7	4491
8	6263
9	8639

Table VIII: Spectral Contrast bands

6.4. Spectral Contrast and MFCC

In this paragraph we give a general analysis of the shape of the spectrum at $t1$, $t2$ and $t3$ by using MFCC and Spectral Contrast features. This analysis offers us a more detailed interpretation of the shift of the energy towards high frequencies.

MFCC coefficients capture the smoothness/irregularity of the spectrum. We computed 13 coefficients. The first coefficients are related to the energy of slowly varying components of the spectrum, and viceversa for the last ones. We can see from Figure 11 that there is a large variation in almost each MFCC coefficient at each finishing step. In figure 12, the values of the MFCC coefficients are shown, from the second to the last (since the first component does not provide relevant information). The analysis show a prominent general variation in the shape of the spectrum along the three finishing steps. In order to better understand this change, we refine the processing by analyzing the behavior for single bands. For this purpose we use the Spectral Contrast.

We recall that the Spectral Contrast is related to the difference in magnitude of the spectrum between the most prominent peak and valley for each subband. The central frequencies of the subbands are given in Table VIII. We can see from Figure 13 that this feature consistently increases for bands at high frequencies, in particular for what concerns the ground-coat application. In Figure 14 the value of the Spectral Contrast for these bands over the three steps is shown. It is worth noticing that for high frequencies (starting from band 4) the Spectral Contrast at step t2 is always larger than that at step t1. We attribute this to the fact that spectral peaks in these bands are magnified by the ground coat.

7. Conclusions

In this work we proposed and described a methodology for studying the impact of violin construction choices on the timbral behaviour of the musical instrument, and we applied this method to the specific problem of assessing the impact of the finishing process. We did this through a joint analysis on material properties and audio features.

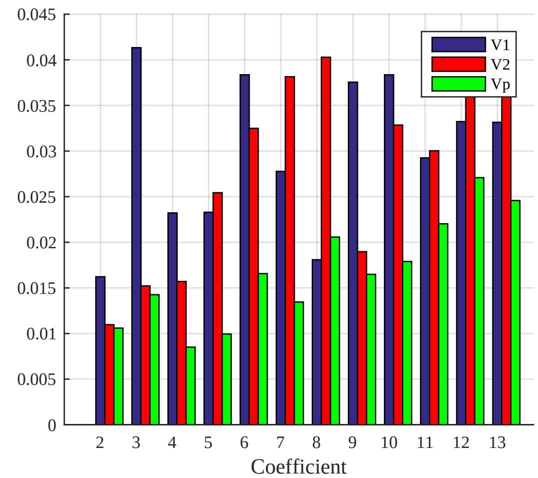

Figure 11: Variation of the MFCC coefficients in three cases: from t1 to t2 (V1), from t2 to t3 (V2) and during the execution of different musicians with a reference instrument(Vp).

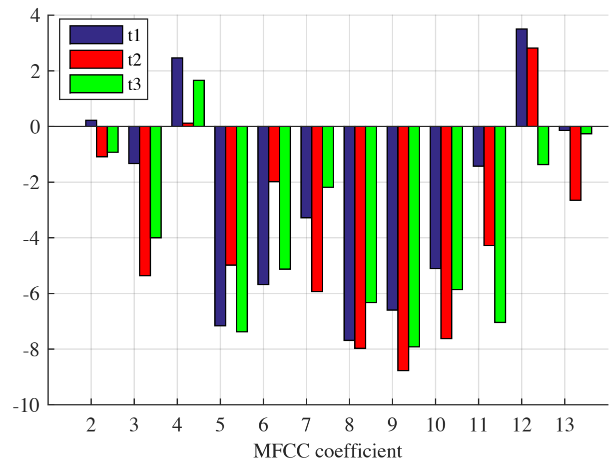

Figure 12: MFCC values

Ours is a perception-oriented feature-based timbral analysis method, which exhibits several advantages over previous solutions in the literature. This method, indeed, gives us a more compact (less redundant) representation of information (descriptors), which is easier to correlate with the results of the analysis of materials.

This analysis brought to light various aspects of the impact of the finishing steps on the timbral characteristics of the violin. We conducted the analysis in three steps, each corresponding to a relevant moment of the finishing process. The first step corresponds to the violin i.e. before the application of the finishing layers. The second one is after the application of the ground

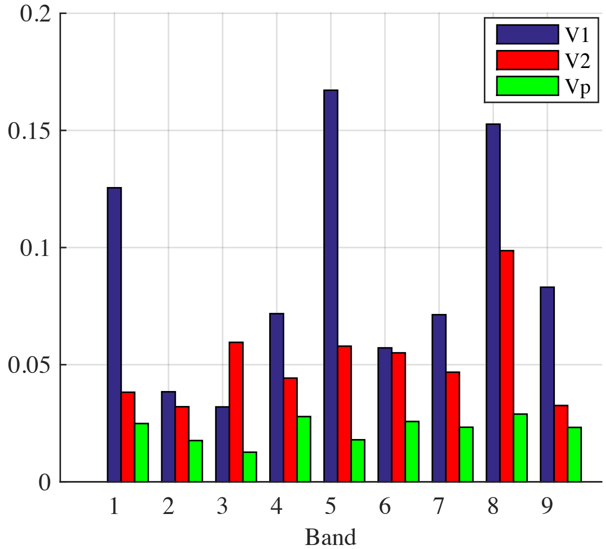

Figure 13: Percentage variation of the Spectral Contrast in three cases: from t1 to t2 (V1), from t2 to t3 (V2) and during the execution of different musicians with a reference instrument(Vp).

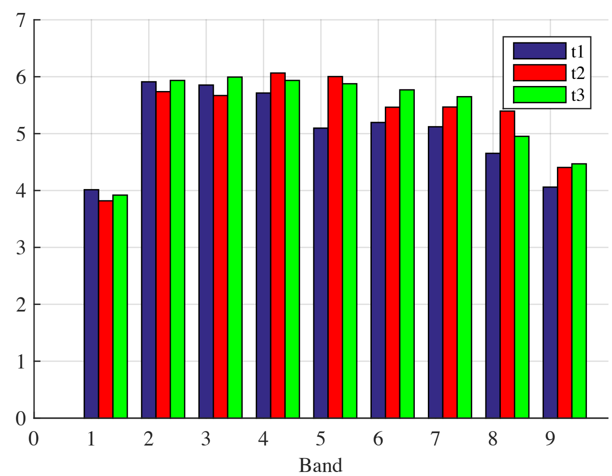

Figure 14: Spectral Contrast values

coat. The last step is after the varnish has been applied and is completely dry.

The analysis on the material, vibroacoustic behavior, and the timbral characteristics of the produced sound revealed that the finishing process has a significant impact on the violin tone quality, and the role played by the ground coat and the varnish is rather different. The untreated violin exhibits a very loud sound, because the body is left completely free to vibrate. The ground coat has greatly reduced the radiated energy, despite the limited thickness of the corresponding "shell". In fact, the calcium caseinate contained in the ground coat recipe turns out to exert a "constriction" on the body's vibrational properties once it is dried, by making the wood surface stiffer. This causes numerous partials to cluster around the bridge-hill region and boosts high frequencies, also confirmed through the vibroacoustic measurements. The ground coat also tends to dampen the low-frequency components of the sound to some extent. The varnish, on the other hand, has a limited impact and only partially reduces the modifications brought by the ground coat. This seems to give the luthier the possibility to fine tune the instrument also during the finishing steps, as also suggested in the literature.

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