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ARTICLE

Analysing Sound Characteristics of Cello and Violin Using Fast Fourier Transform

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Abstract

The unique sound characteristics of music are based on multiple harmonic frequencies that exist within the sound waves. Through Fast Fourier Transform (FFT) software, the wave can be broken down into frequency and amplitude components. Spectrum analysis can be used quantitatively to describe these sound characteristics. In this paper, the frequency range present in the spectrum and the average intensity of the first 10 high notes in the sound are used to classify the sound characteristics of the cello and violin. This is done by generating a frequency (x-axis) and amplitude (y-axis) graph for the sounds of the cello and violin. The frequency and amplitudes are used to calculate 7 descriptors for sound characteristics, namely the centroid ($\bar{f}$) Affinity (A), Brightness or Sharpness (S), Harmonicity (H), Monotony (M), Mean Affinity (MA), and Mean Contrast (MC). The results of the research reveal that quantitative frequency data analysis can generate and map sound characteristics. Quantitative analysis allows the quality of sound characteristics to be transformed into information understood by the computer. Eurostring cello string C2 is the most affinity (having a minimum A value, approaching 1, indicating that f_o and $\bar{f}$ are close). Eurostring violin string D4 have the brightest sound (maximum S value). Stradivarius copy violin strings D4 is the most harmonic (having a minimum H value, approaching 0). Eurostring cello string C2 shows harmonics present in most successive reductions (negative M) after f_o. The MA value of Spicato cello C2 indicates dense secondary sound and is close to $\bar{f}$. The maximum MC value of Eurostring violin string D4 indicates normalized amplitude for its high-secondary frequency.

Keywords: Acoustic spectra, Cello, Violin, Fast Fourier Transform (FFT), Frequency spectrum, Sound characteristics, High notes, Harmonics

1. Introduction

Complex waves are the sum of harmonic and non-harmonic wave components (Plomp, 1976). The sound from musical instruments results from the sensation of individual notes with their corresponding pitches (corresponding to the fundamental frequency, f_o). Specific sound characteristics depend on the relative amplitudes of these components. In this paper, a comparison between the frequencies of the cellos and violins are investigated using PicoScope oscilloscope and Adobe

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Audition. The aim of this paper is to examine sound signals and time-frequency analysis (TFA) of the cellos and violins. The Fast Fourier Transform (FFT) is used to perform TFA on the sound signals from the cellos and violins. The time-frequency content of the sound signals is visualized by creating spectrogram images using Adobe Audition. These spectrograms are used to identify the peaks produced by the sound signals. Time-frequency spectrograms display the changing frequency content of sound signals over time.

The human ear is unable to distinguish single harmonics in complex sounds, and identification of individual components is nearly impossible when listening to notes in a musical context (Plomp, 1976). There are many features used to represent sound signals, which reveal differences in musical instrument sounds (Deng et al., 2008; Essid et al., 2006; Herrera-Boyer et al., 2003, 2006; Klapuri & Davy, 2006). While sound signals are characterized by time, spectra are characterized by frequency. Frequency spectra are a widely used frequency analysis technique, and they are extensively used for sound signals in which statistical properties change with time (Mallat, 2009). Frequency changing with time is observed in the time-frequency domain (with continuous wavelet analysis where sound signals are decomposed into fundamental and high-frequency components).

Most sound analysis and re-synthesis are investigating tone systems (Hamdan et al., 2020). The use of frequency in musical sound signals can be divided into two cases based on the presentation. In the first presentation, the emphasis is placed on extracting instantaneous frequencies from sinusoidal waveforms. Instantaneous frequencies of sound signals can be extracted using the FFT and are displayed as frequency versus amplitude. This characterizes the frequency modulation of sound signals. In the second presentation, it involves the time-frequency plane. Feature frequency peaks are extracted for audio, including musical instrument sounds (Lin et al., 2005). Rhythm, tempo, and pitch are typical musical terms that can be quantitatively explained. Traditionally, sound characteristics are aspects of music that are described qualitatively. By analysing different frequencies, a quantitative approach to assessing sound characteristics can be performed. Practically, a quantitative approach is used to understand and manipulate sound. Unique sound characteristics for an instrument are generated by the presence of high notes in the sound. Each note of an instrument has a specific fundamental frequency, f_o (the lowest frequency in a sound signal). Harmonic frequencies are integer multiples of f_o. Essentially, the note consists of a series of different-frequency sinusoidal waves that combine to form the sound wave.

The addition of different frequencies from sinusoidal waves produces distinct sound characteristics as perceived by the ear. To analyse sound characteristics, one can examine the frequency spectrum of the sound wave, which displays both harmonic and non-harmonic frequencies in the sound, along with their corresponding amplitudes (in decibels) for each frequency. From this spectrum, the most dominant frequency in the wave can be determined and compared to other frequencies. This comparison yields quantitative data that can be used to explain the sound characteristics of different musical instruments. To generate the spectrum, wave data must be transformed from the time domain to the frequency domain. This essentially breaks down the sound wave into its frequency components (both harmonic and non-harmonic) and can be accomplished using FFT. This paper uses FFT software as a quantitative method to analyse the sound characteristics of the cellos and violins. Quantitative analysis allows the quality of sound characteristics to be transformed into information understood by the computer. In this way, the analysis of sound characteristics can be automated and applied effectively in sound engineering and music production technology. Using FFT software, sound characteristics for musical instruments can be created by combining sound signals from various frequencies present in the instrument's wave. Spectrum analysis techniques are widely used in sound engineering, where frequencies can be added, changed, or removed to manipulate specific sound characteristics. FFT-based feature classification software is also used in song recognition technology and applications like Shazam (Jovanovic, 2020). Quantitative descriptions of sound characteristics become especially useful in the development of technology for the deaf or hearing-impaired. Identifying sound characteristics through FFT and spectrum analysis software can be used to transform feature elements into alternative stimulus signals that allow individuals to understand sound properties without hearing them directly (González and Prati 2019, 2021; 2022a; 2022b, 2023). The frequency versus amplitude variables is used to calculate 7 descriptors for sound characteristics, namely the centroid ($\bar{f}$), Affinity (A), Brightness or Sharpness (S), Harmonicity (H), Monotony (M), Mean Affinity (MA), and Mean Contrast (MC) (González & Prati, 2019). The applications of FFT for timbral characterization in woodwind instruments was studied by Gonzalez and Prati (2021) whereas the acoustic descriptors for characterization of musical timbre using the FFT was studied by Gonzalez and Prati (2022a). Acoustic analysis of musical timbre of wooden aerophones was studied by Gonzalez and Prati (2022b) and similarity of musical timbres using FFT-acoustic descriptor analysis and machine learning was studied by Gonzalez and Prati (2023). The 7 descriptors that explain sound characteristics in terms of normalized frequency and amplitude are as follows:

1. The spectral centroid ($\bar{f}$) is a measure used in digital signal processing to characterise a spectrum. It indicates where the centre of mass of the spectrum is located. Perceptually, it has a robust connection with the impression of brightness of a sound. It is sometimes called centre of spectral mass. It is calculated as the weighted mean of the frequencies present in the signal, determined using a Fast Fourier Transform, with their magnitudes as the weights.
2. The measurement of f_o against the average frequency $\bar{f}$ is called Affinity (A).
3. The measurement of amplitude a_o against the collection of amplitudes a_i is called Brightness or Sharpness (S).
4. The descriptor indicating the approximation of secondary pulses to the integer multiples of f_o is called Harmonicity (H).
5. The envelope descriptor through the average slope in the collection of pulses is called Monotony (M).
6. The measurement of frequency dispersion against $\bar{f}$ is called Mean Affinity (MA).
7. The measurement of the average amplitude of the pulse collection is called Mean Contrast (MC).

Table 1 provides equations for sound characteristics using FFT based on amplitude and frequency (Gonzalez & Prati, 2022a).

The work on wind instruments such as Clarinet, Bassoon, Transverse Flute, and Oboe has been done by (González and Prati 2019, 2021; 2022a; 2022b, 2023) however, to our knowledge no research has been conducted to compare the sound characteristics between cellos and violins. All descriptor calculations are done using a Python program. (Musib et al., 2024).

Table 1. Descriptor for sound characteristics based on amplitude and frequency.

Description	Formula
Centroid, $\bar{f}$	$\bar{f}\equiv\frac{\sum_{i=1}^{N}a_if_i}{\sum_{i=1}^{N}a_i}$
Affinity, A	$A\equiv\frac{1\sum_{i=1}^{N}a_if_i}{f_0\sum_{i=1}^{N}a_i}=\frac{\bar{f}}{f_0}$
Sharpness, S	$S\equiv\frac{a_0}{\sum_{i=1}^{N}a_i}$
Harmonicity, H	$H\equiv\sum_{j=1}^{N}\left(\frac{f_j}{f_0}-\left\lfloor\frac{f_j}{f_0}\right\rfloor\right)$
Monotony, M	$M\equiv\frac{f_0}{N}\sum_{j=1}^{N}\left(\frac{a_{j+1}-a_j}{f_{j+1}-f_j}\right)$
Mean affinity, MA	$MA\equiv\frac{\sum_{i=1}^{N}\lvert f_i-\bar{f}\rvert}{Nf_0}$
Mean contrast, MC	$MC\equiv\frac{1}{N}\sum_{j=1}^{N}\lvert a_0-a_j\rvert$ f_o is fundamental frequency f_i is the ith frequency a_o is fundamental amplitude a_i is the ith amplitude $\left\lfloor\frac{f_j}{f_0}\right\rfloor$ denote the integer part

2. Methodology

The acoustic spectra of the cellos and violins (all using 'Dominant' strings) were captured using PicoScope oscilloscopes to investigate the fundamental and overtone frequencies. Fig. 1 is a schematic diagram for sound recording using the PicoScope oscilloscope (Hamdan et al., 2021). Fig. 2 shows the cello (Spicato) and violin (Eurostring). The cello consists of strings C2 (0.06 kHz), G2 (0.09 kHz), D3 (0.14 kHz), and A3 (0.22 kHz), while the violin consists of strings G3 (0.19 kHz), D4 (0.29 kHz), A4 (0.44 kHz), and E5 (0.65 kHz). The sound intensity of the cellos and violins remained constant throughout the recording process to ensure no effect on the results. Different intensity and harmonics or sub-harmonics (overtones) distinguish each instrument characteristics. Most important, this work showed all the range of available frequencies at a specific time. The frequencies that are present in the signal are easily identified. To maintain the sound intensity levels of the cellos and violins, the string was plucked with a plectrum and not by bowing. If this is not achieved the sound produce will have different intensity level. The different intensity level produced will not affect the frequency but will affect the intensity level. To avoid this a professional player was employed to do the plucking. For each recording, the entire recorded waveform and frequency spectrum was selected and saved.

The sound was measured at the studio hall of Universiti Malaysia Sarawak (UNIMAS). The microphone was held above the top surface along the axis of symmetry at a distance of 20 cm. In this study, the audio signal derived from the plucking by an expert player is recorded. The audio signal is recorded in mono, at 24-bit resolution and 48 kHz sampling rate. The audio signal is recorded with the aid of a digital audio interface in a. wav format.

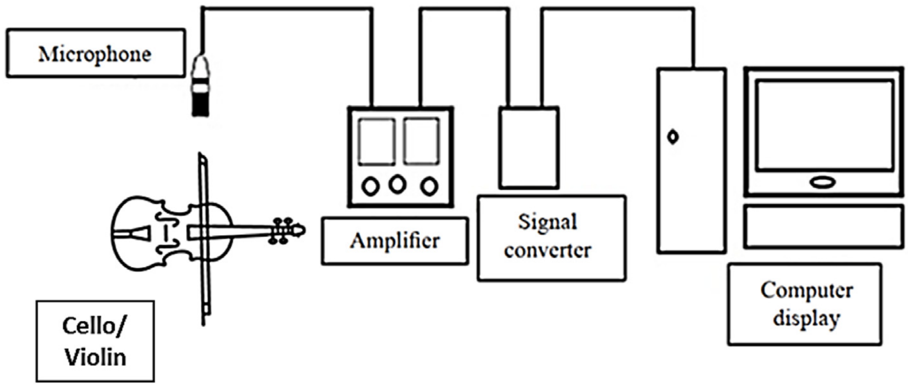


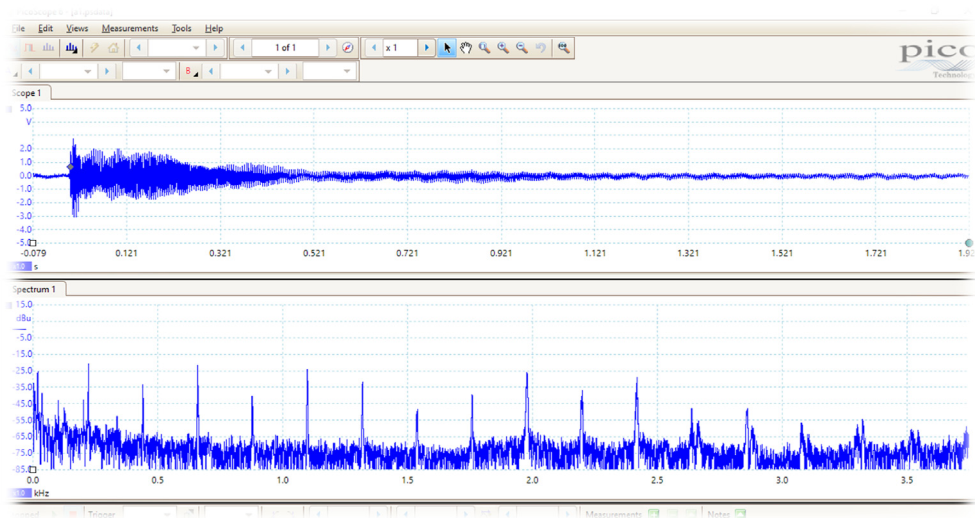
Fig. 1. Schematic diagram for recording using signal converter (PicoScope).

Fig. 2. The cello and violin.

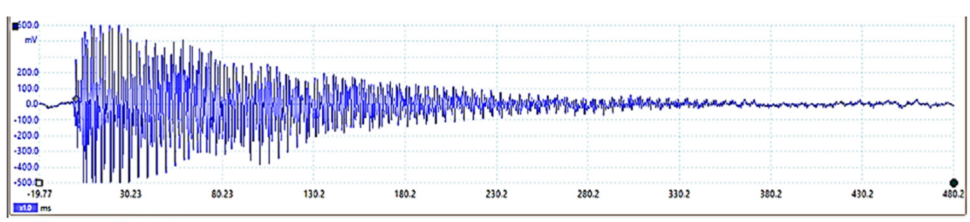
To ensure the recorded audio signal is at the optimum level, audio signal calibration of the recording system is carried out. A test tone of 1 kHz sine wave is used in calibrating the recording system. Here the "unity" calibration level is at +4 dBu or −10 dBV and is read by the recording device at 0 VU. In this regard, the European Broadcasting Union (EBU) recommended the digital equivalent of 0 VU is that the test tone generated to the recording device of the experimentation is recorded at −18 dBFS (digital) or +4 dBu (analogue) which is equivalent to 0 VU. In this thorough procedure of calibration, no devices are unknowingly boosting or attenuating its amplitude in the signal chain at the time of the recording is carried out. The recording apparatus was the Steinberg UR22mkII audio interface, Audio-Technica AT4050 microphone, XLR cable (balance), with microphone position on axis (20 cm), and microphone setting with low cut (flat) 0 dB. The PicoScope computer software (Pico Technology, 3000 series, Eaton Socon, UK) was used to view and analyse the time signals from PicoScope oscilloscopes (Pico Technology, 3000 series, Eaton Socon, UK) and data loggers for real time signal acquisition. PicoScope software enables analysis using FFT, a spectrum analyser, voltage-based triggers, and the ability to save/load waveforms to a disc. The cello/violin was placed to where the sound could be captured with minimum interference. The amplifier (Behringer Powerplay Pro XL, Behringer, China) ensured the sound capture was loud enough to be detected by the signal converter. The uniqueness of our research is visualising the sound sonically through PicoScope oscilloscopes and Adobe Audition 2023 (Adobe Inc., version 23.3, California, USA). The sound spectra are obtained from PicoScope measurements. In this work, the fundamental and overtone frequency were measured, which is also called the timbre. Fourier transformation determines fundamentals, harmonics, and subharmonics. Different intensity and harmonics or subharmonics (overtones) distinguish each instrument characteristics. In this sense, the difference is necessary to describe the different between cellos and violins. Similar set up is used for signal processing to obtain the sound spectrogram measured using Adobe Audition with the amplifier connected directly to the computer (without signal converter/PicoScope).

The Fast Fourier Transform (FFT) was generate by the PicoScope computer software (Pico Technology, 3000 series, Eaton Socon, UK) (see Fig. 3a). Fig. 3b is a typical sound signal (ms versus mV) from the PicoScope oscilloscope (obtain from Fig. 3a). mV-millivolt is a measure of electrical potential produce by the sound. Fig. 3c is a typical frequency spectrum (kHz versus dBu) from the PicoScope oscilloscope (obtain from Fig. 3a). dBu-decibel units specifically for measuring voltage. dBu is dB relative to 0.775 V; such that 0dBu = 0.775 V. The frequency spectrum displays all the high notes present in the entire sound sample. Peaks indicate dominant harmonic or secondary frequencies in each sound signal waveform. Differences in shape and distribution for each spectrum explain the distinct sound characteristics of the cellos and violins.

This approach was chosen because most sound analysis and re-synthesis are investigating tone systems (Hamdan et al., 2020). The data from the measurements helps in understanding the structure of the sound. The frequency has been measured using oscilloscope, whereas the time frequency has been measured using Adobe Audition. All the work mentions above measured the fundamental frequency and the overtone frequency. Frequency spectrum plots enable sound characteristic analysis because they display the presence of frequency



a)



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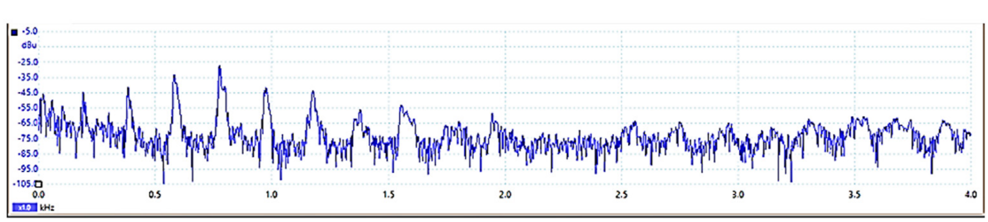

c)

Fig. 3. (a) Typical sound signals (ms versus mV) and frequency spectra (kHz versus dBu) from the PicoScope oscilloscope. (b) Typical sound signals (ms versus mV) from the PicoScope oscilloscope. mV-millivolt is a measure of electrical potential (obtain from (a)). (c)Typical frequency spectra (kHz versus dBu) from the PicoScope oscilloscope. dBu-decibel units specifically for measuring voltage. dBu is dB relative to 0.775 V; such that 0dBu = 0.775 V (obtain from (a)).

components in the sound sample. All descriptor calculations are done using a Python program. (Musib et al., 2024).

3. Results and discussion

Figs. 4 and 5 display the frequency spectra (kHz) of cello strings C2 (0.06), G2 (0.09), D3 (0.14), and A3 (0.22), from Spicato and Eurostring respectively.

Figs. 6 and 7 display the frequency spectra (kHz) of violin strings G3 (0.19), D4 (0.28), A4 (0.43), and E5 (0.65), from Eurostring and Stradivarius copy violins respectively.

Tables 2 and 3 show the frequency f_i along with the amplitude a_i for Spicato and Eurostring cello strings C2, G2, D3, and A3 respectively obtained from Figs. 4 and 5. Tables 4 and 5 show the frequency f_i along with the amplitude a_i for Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5, obtained from Figs. 6 and 7.

Tables 6 and 7 show the frequency and frequency/f_o for Spicato and Eurostring cello strings C2, G2, D3, and A3 respectively obtained from Tables 2 and 3. Tables 8 and 9 show the frequency and frequency/f_o for Eurostring and Stradivarius copy violin strings

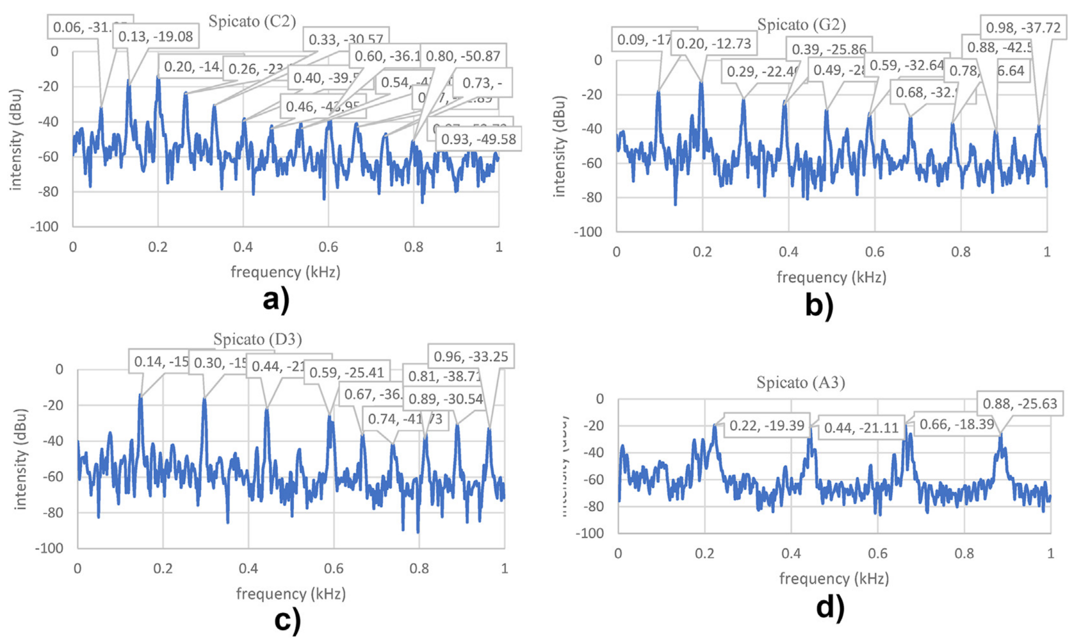

Fig. 4. (a) The frequency spectra for Spicato cello string C2 (0.06 kHz). (b) The frequency spectra for Spicato cello string G2 (0.09 kHz). (c) The frequency spectra for Spicato cello string D3 (0.14 kHz). (d) The frequency spectra for Spicato cello string A3 (0.22 kHz).

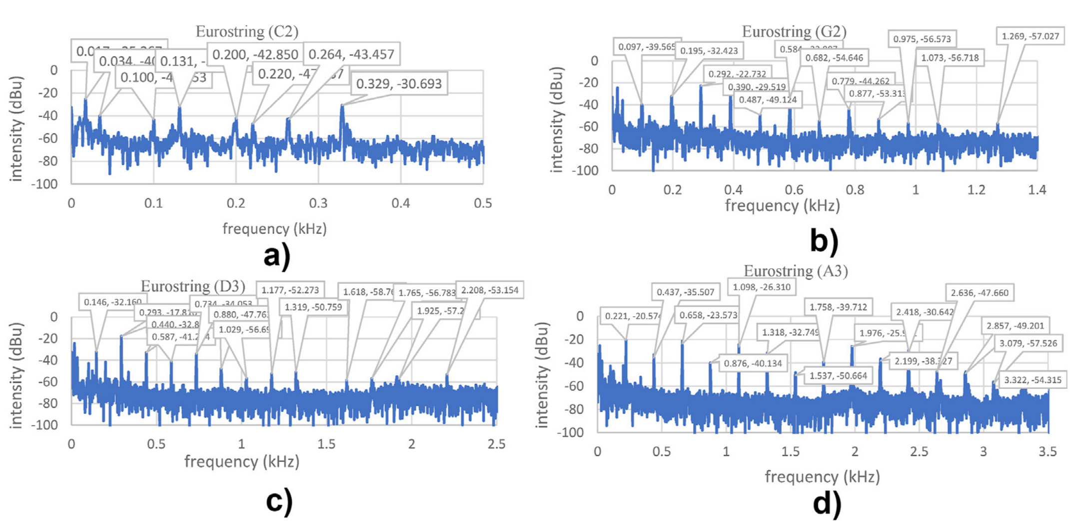

Fig. 5. (a)The frequency spectra for Eurostring cello string C2 (0.06 kHz). (b) The frequency spectra for Eurostring cello string G2 (0.09 kHz). (c) The frequency spectra for Eurostring cello string D3 (0.14 kHz). (d) The frequency spectra for Eurostring cello string A3 (0.22 kHz).

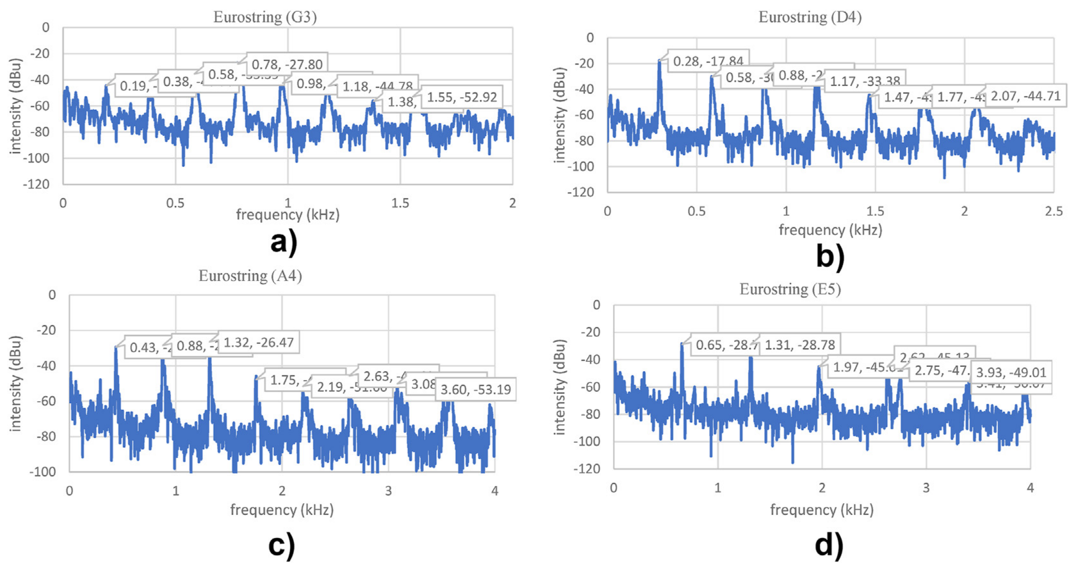

Fig. 6. (a) The frequency spectra of Eurostring violin string G3 (0.19 kHz). (b) The frequency spectra of Eurostring violin string D4 (0.28 kHz). (c) The frequency spectra of Eurostring violin string A4 (0.43 kHz). (d) The frequency spectra of Eurostring violin string E5 (0.65 kHz).

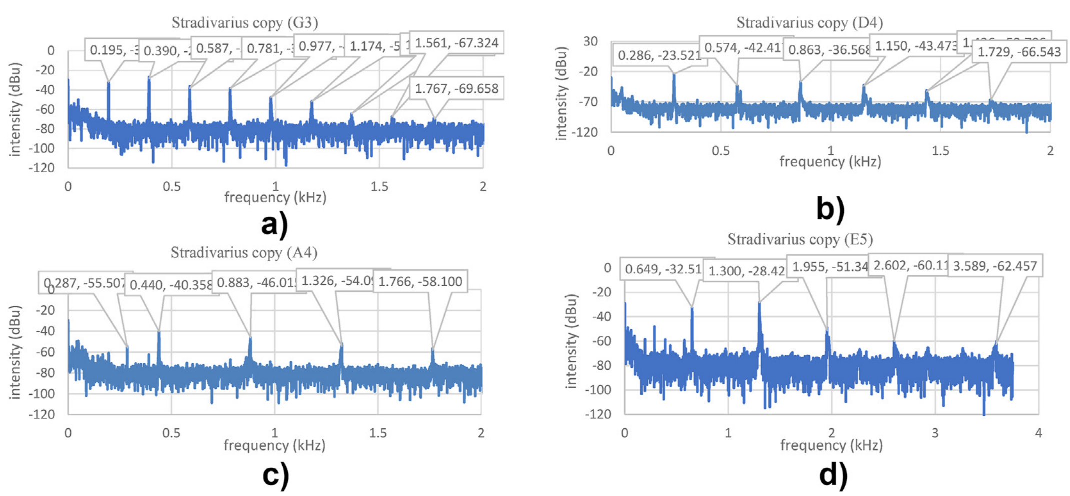

Fig. 7. (a) The frequency spectra of Stradivarius copy violin string G3 (0.19 kHz). (b) The frequency spectra of Stradivarius (copy) violin string D4 (0.28 kHz). (c) The frequency spectra of Stradivarius copy violin string A4 (0.44 kHz). (d) The frequency spectra of Stradivarius copy violin string E5 (0.65 kHz).

G3, D4, A4, and E5 respectively obtained from Tables 4 and 5 All cellos and violins strings display integer multiples of f_o for most of the higher harmonics.

The normalized amplitude a_{norm} is calculated based on the maximum amplitude from the spectra from Tables 2–5.

$$\text{Normalized amplitude } a_{norm} = \frac{\text{amplitude } (a_i)}{\text{maximum amplitude}} \tag{1}$$

where $a_{i=n} = 1,2,3 \ldots N$.

Figs. 8 and 9 display the frequency versus normalized amplitude for Spicato and Eurostring cellos respectively. Figs. 10 and 11 display the frequency versus normalized amplitude for Eurostring and Stradivarius copy violins respectively. In Fig. 8, Spicato cello C2 and G2 exhibit maximum amplitude at the third and second harmonic respectively while both D3 and A3 show maximum amplitude at f_o.

In Fig. 9, Eurostring cello C2 and A3 exhibit maximum amplitude at f_o while both G2 and D3 show maximum amplitude the third and second harmonic respectively.

Table 2. The frequency f_i (kHz) along with the amplitude a_i (dBu) for Spicato cello strings C2, G2, D3, and A3.

C2		G2		D3		A3	
f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)
0.06	−31.85	0.090	−17.82	0.14	−15.24	0.22	−19.39
0.13	−16.32	0.19	−12.73	0.29	−15.93	0.44	−19.61
0.20	−13.4	0.29	−22.40	0.44	−21.90	0.66	−20.10
0.26	−23.35	0.39	−23.72	0.58	−25.41	0.88	−25.63
0.33	−30.57	0.48	−28.9	0.66	−36.32		
0.40	−38.22	0.58	−30.79	0.73	−42.01		
0.46	−42.22	0.68	−32.98	0.81	−36.65		
0.53	−40.50	0.78	−37.51	0.89	−32.82		
0.60	−35.37	0.88	−40.72	0.96	−33.25		
0.66	−40.94	0.92	−45.33				
0.73	−48.29	0.98	−37.72				
0.79	−50.87						
0.86	−53.04						

Table 3. The frequency f_i (kHz) along with the amplitude a_i (dBu) for Eurostring cello strings C2, G2, D3, and A3.

C2		G2		D3		A3	
f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)
0.01	−25.26	0.09	−39.56	0.14	−32.16	0.22	−20.57
0.03	−40.01	0.19	−32.42	0.29	−17.81	0.43	−35.50
0.1	−43.35	0.29	−22.73	0.44	−32.87	0.65	−23.57
0.13	−32.15	0.39	−29.51	0.58	−41.28	0.87	−40.13
0.2	−42.85	0.48	−49.12	0.73	−34.05	1.09	−26.31
0.22	−47.03	0.58	−33.98	0.88	−47.76	1.31	−32.74
0.26	−43.45	0.68	−54.64	1.02	−56.69	1.53	−50.66
0.32	−30.69	0.77	−44.26	1.17	−52.27	1.75	−39.71
		0.87	−53.31	1.31	−50.75	1.97	−25.90
		0.97	−56.57	1.61	−58.76	2.19	−38.32
		1.03	−56.71	1.76	−56.78	2.41	−30.64
		1.26	−57.02	1.92	−57.29	2.63	−47.66
				2.2	−53.15	2.85	−49.20
						3.07	−57.52
						3.32	−54.31

Table 4. The frequency f_i (kHz) along with the amplitude a_i (dBu) for Eurostring violin strings G3, D4, A4, and E5.

G3		D4		A4		E5	
f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)
0.19	−44.36	0.29	−17.84	0.44	−29.36	0.65	−28.76
0.38	−40.90	0.58	−30.36	0.88	−28.43	1.31	−28.78
0.58	−35.39	0.88	−28.48	1.32	−26.47	1.97	−45.01
0.78	−27.80	1.17	−33.38	1.75	−47.75	2.62	−45.13
0.98	−42.47	1.47	−45.73	2.19	−51.6	2.75	−47.43
1.18	−44.78	1.77	−45.46	2.63	−45.62	3.41	−56.67
1.38	−56.41	2.07	−44.71	3.08	−50.10	3.93	−49.01
1.55	−52.92			3.60	−53.19		

In Fig. 10, Eurostring violin, both D4 and E5 display maximum amplitude at f_o, while G3 and A4 each exhibit maximum amplitude at the fourth and third harmonics respectively.

In Fig. 11, Stradivarius copy violin, D4 display maximum amplitude at f_o, while G3, A4 and E5 each exhibit maximum amplitude at the second harmonics respectively.

From Fig. 8, f_o is highly prominent in the Spicato cello strings D3 and A3, while the third harmonic and the second harmonic are very prominent in the C2 and G2 strings respectively. From Fig. 9, f_o is highly prominent in the Eurostring cello strings A3, while the third harmonic and the second harmonic are very prominent in the G2 and D3, and the sub-harmonics are very prominent in the C2. From

Table 5. The frequency f_i (kHz) along with the amplitude a_i (dBu) for Stradivarius (copy) violin strings G3, D4, A4, and E5.

G3		D4		A4		E5	
f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)	f_i (kHz)	a_i (dBu)
0.19	−32.02	0.28	−23.52	0.87	−55.50	0.64	−32.51
0.38	−28.24	0.57	−42.41	0.44	−40.35	1.3	−28.42
0.58	−38.23	0.86	−36.56	0.88	−46.01	1.95	−51.34
0.78	−38.43	1.15	−43.47	1.32	−54.09	2.6	−60.11
0.97	−47.72	1.43	−52.70	1.76	−58.1	3.58	−62.45
1.17	−51.72	1.79	−66.54				
1.36	−64.35						
1.56	−67.32						
1.76	−69.65						

Table 6. The frequency and frequency/f_o for Spicato cello strings C2, G2, D3, and A3.

C2		G2		D3		A3	
Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o
0.06	1.00 ± 0.08	0.09	1.00 ± 0.45	0.14	1.00 ± 0.49	0.22	1.00 ± 0.03
0.13	1.97 ± 0.08	0.19	2.01 ± 0.45	0.29	2.00 ± 0.49	0.44	1.99 ± 0.03
0.20	3.02 ± 0.08	0.29	3.01 ± 0.45	0.44	2.98 ± 0.49	0.66	2.98 ± 0.03
0.26	3.99 ± 0.08	0.39	3.99 ± 0.45	0.58	3.97 ± 0.49	0.88	3.97 ± 0.03
0.33	4.99 ± 0.08	0.48	4.99 ± 0.45	0.66	4.49 ± 0.49		
0.40	6.05 ± 0.08	0.58	6.01 ± 0.45	0.73	4.96 ± 0.49		
0.46	7.02 ± 0.08	0.68	6.97 ± 0.45	0.81	5.49 ± 0.49		
0.53	8.05 ± 0.08	0.78	7.99 ± 0.45	0.89	5.99 ± 0.49		
0.60	9.08 ± 0.08	0.88	9.01 ± 0.45	0.96	6.49 ± 0.49		
0.66	10.02 ± 0.08	0.92	9.45 ± 0.45				
0.73	11.08 ± 0.08	0.98	10.03 ± 0.45				
0.79	12.02 ± 0.08						
0.86	13.02 ± 0.08						
0.93	14.05 ± 0.08						

Table 7. The frequency and frequency/f_o for Eurostring cello strings C2, G2, D3, and A3.

C2		G2		D3		A3	
Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o
0.01	0.1 ± 0.08	0.09	1 ± 0.45	0.14	1 ± 0.49	0.22	1 ± 0.05
0.03	0.3 ± 0.08	0.19	2.11 ± 0.45	0.29	2.07 ± 0.49	0.43	1.95 ± 0.05
0.1	1 ± 0.08	0.29	3.22 ± 0.45	0.44	3.14 ± 0.49	0.65	2.95 ± 0.05
0.13	1.3 ± 0.08	0.39	4.33 ± 0.45	0.58	4.14 ± 0.49	0.87	3.95 ± 0.05
0.2	2 ± 0.08	0.48	5.33 ± 0.45	0.73	5.21 ± 0.49	1.09	4.95 ± 0.05
0.22	2.2 ± 0.08	0.58	6.44 ± 0.45	0.88	6.28 ± 0.49	1.31	5.95 ± 0.05
0.26	2.6 ± 0.08	0.68	7.55 ± 0.45	1.02	7.28 ± 0.49	1.53	6.95 ± 0.05
0.32	3.2 ± 0.08	0.77	8.55 ± 0.45	1.17	8.35 ± 0.49	1.75	7.95 ± 0.05
		0.87	9.66 ± 0.45	1.31	9.35 ± 0.49	1.97	8.95 ± 0.05
		0.97	10.77 ± 0.45	1.61	11.5 ± 0.49	2.19	9.95 ± 0.05
		1.03	11.44 ± 0.45	1.76	12.57 ± 0.49	2.41	10.95 ± 0.05
		1.26	14 ± 0.45	1.92	13.71 ± 0.49	2.63	11.95 ± 0.05
				2.2	15.71 ± 0.49	2.85	12.95 ± 0.05
						3.07	13.95 ± 0.05
						3.32	15.09 ± 0.05

Fig. 10, f_o is highly prominent in the Eurostring violin strings D4 and E5, while the fourth harmonic and the third harmonic are very prominent in the G3 and A4 strings respectively. From Fig. 11, f_o is highly prominent in the Stradivarius violin strings D4 and A4, while the second harmonic is very prominent in the A4 and E5 strings.

We start by characterizing the sound characteristics of the cellos and violins based on two features displayed in the harmonic spectra, the distribution of existing harmonic frequencies and the intensity of harmonic frequencies. For this study, the average intensity of the top 10 high notes (the first 10 partials) is examined. Each peak is considered as a data point

Table 8. The frequency and frequency/f_o for Eurostring violin strings G3, D4, A4, and E5.

G3		D4		A4		E5	
Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f f_o	Frequency (kHz)	Frequency/f_o
0.19	1.00 ± 0.26	0.29	1.00 ± 0.13	0.44	1.00 ± 0.18	0.65	1.00 ± 0.24
0.38	2.00 ± 0.26	0.58	2.00 ± 0.13	0.88	2.00 ± 0.18	1.31	2.01 ± 0.24
0.58	3.05 ± 0.26	0.88	3.03 ± 0.13	1.32	3.00 ± 0.18	1.97	3.03 ± 0.24
0.78	4.10 ± 0.26	1.17	4.03 ± 0.13	1.75	3.97 ± 0.18	2.62	4.03 ± 0.24
0.98	5.15 ± 0.26	1.47	5.06 ± 0.13	2.19	4.97 ± 0.18	2.75	4.23 ± 0.24
1.18	6.21 ± 0.26	1.77	6.10 ± 0.13	2.63	5.97 ± 0.18	3.41	5.24 ± 0.24
1.38	7.26 ± 0.26	2.07	7.13 ± 0.13	3.08	7.00 ± 0.18	3.93	6.04 ± 0.24
1.55	8.15 ± 0.26			3.60	8.18 ± 0.18		

Table 9. The frequency and frequency/f_o for Stradivarius copy violin strings G3, D4, A4, and E5.

G3		D4		A4		E5	
Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f_o	Frequency (kHz)	Frequency/f f_o	Frequency (kHz)	Frequency/f_o
0.19	1 ± 0.26	0.28	1 ± 0.13	0.87	1.97 ± 0.18	0.64	1 ± 0.24
0.38	2 ± 0.26	0.57	2.03 ± 0.13	0.44	1 ± 0.18	1.3	2.03 ± 0.24
0.58	3.05 ± 0.26	0.86	3.07 ± 0.13	0.88	2 ± 0.18	1.95	3.04 ± 0.24
0.78	4.10 ± 0.26	1.15	4.10 ± 0.13	1.32	3 ± 0.18	2.6	4.06 ± 0.24
0.97	5.10 ± 0.26	1.43	5.10 ± 0.13	1.76	4 ± 0.18	3.58	5.59 ± 0.24
1.17	6.15 ± 0.26	1.79	6.39 ± 0.13				
1.36	7.15 ± 0.26						
1.56	8.21 ± 0.26						
1.76	9.26 ± 0.26						

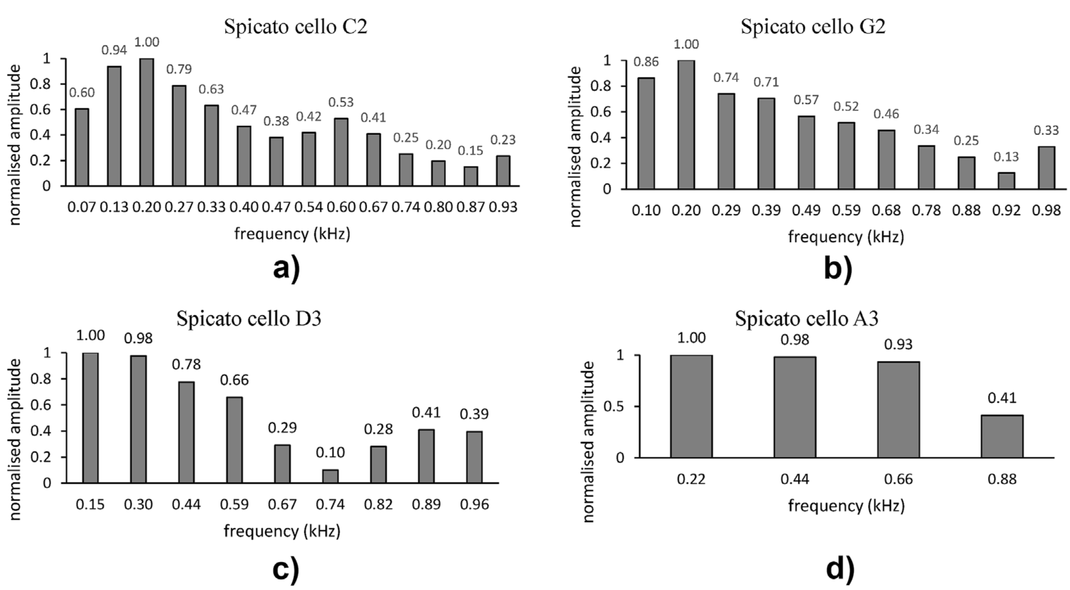

Fig. 8. (a) Normalized amplitude versus frequency (kHz) for Spicato cello C2 string. (b) Normalized amplitude versus frequency (kHz) for Spicato cello G2 string. (c) Normalized amplitude versus frequency (kHz) for Spicato cello D3 string. (d) Normalized amplitude versus frequency (kHz) for Spicato cello A3 string.

representing the corresponding frequency and intensity. Data for the intensity of each peak is obtained for the first 10 high notes, and the average for the first 10 high notes is calculated for a quantitative assessment of the brightness of sound characteristics (denser harmonics indicate very bright sound characteristics). In music, there are many terms that can be used to describe the quality of sound characteristics. Qualitative terms to illustrate sound characteristics are a highly subjective process because the perception of each individual is different and often associates sound with different descriptors.

In this research, sound characteristics produced by the cellos were based on the tradition of

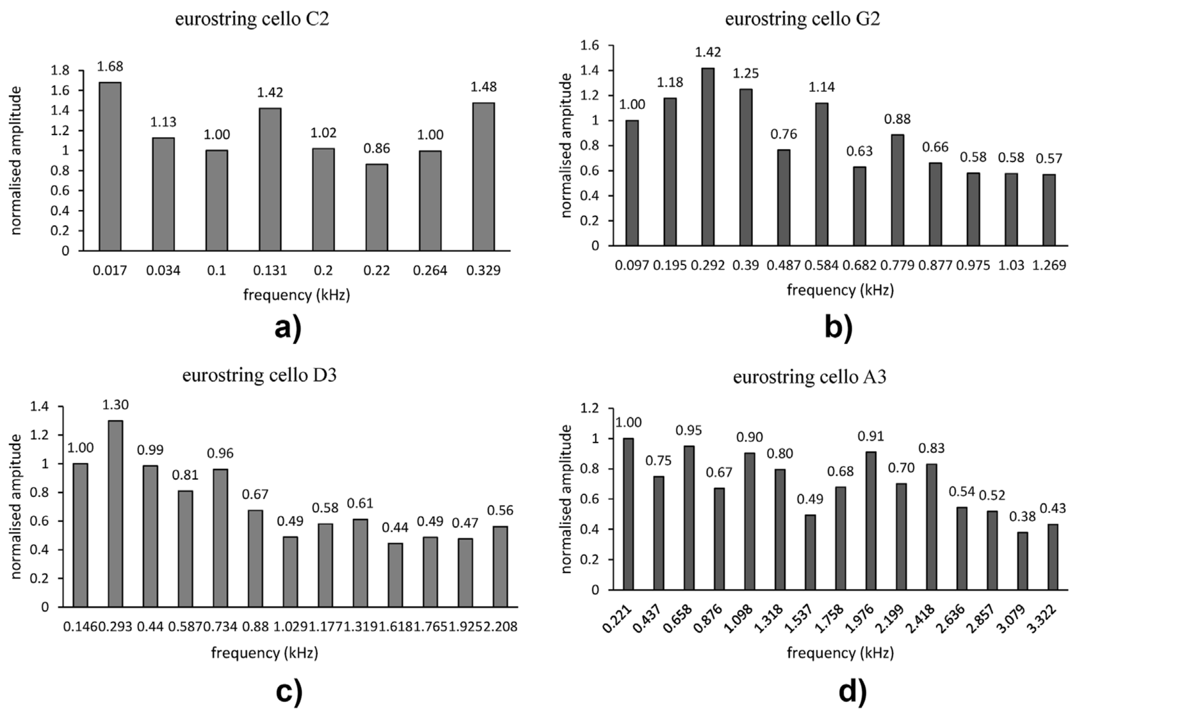

Fig. 9. (a) Normalized amplitude versus frequency (kHz) for Eurostring cello C2 string. (b) Normalized amplitude versus frequency (kHz) for Eurostring cello G2 string. (c) Normalized amplitude versus frequency (kHz) for Eurostring cello D3 string. (d) Normalized amplitude versus frequency (kHz) for Eurostring cello A3 string.

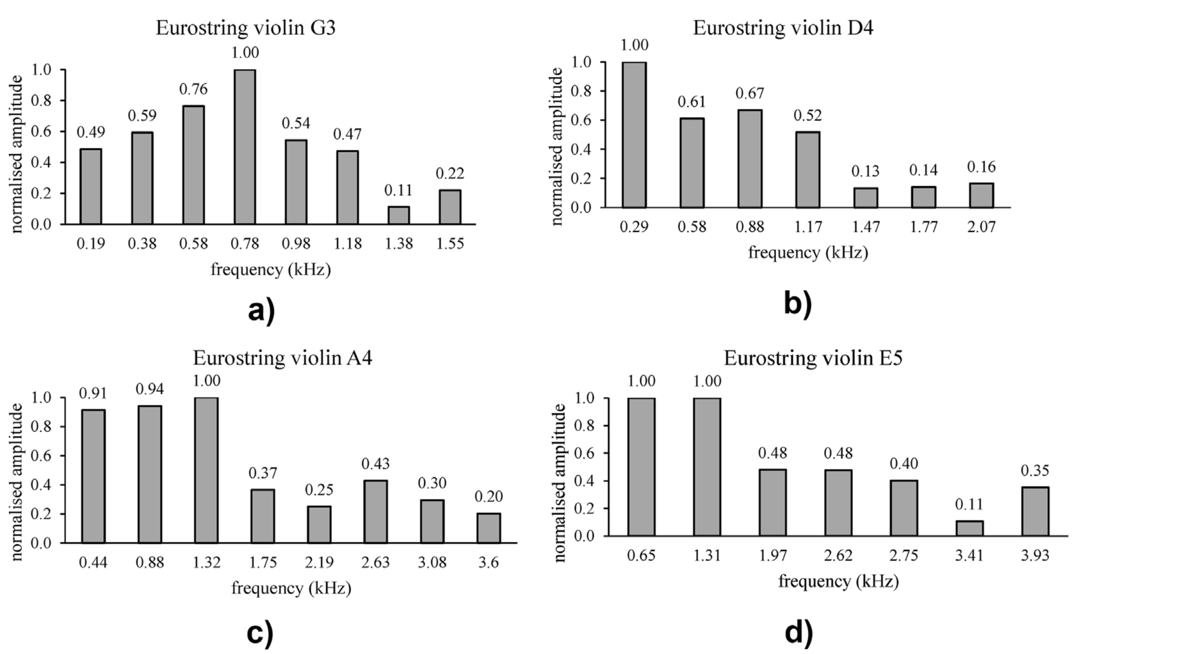

Fig. 10. (a) Normalized amplitude versus frequency (kHz) for Eurostring violin G3 string.(b) Normalized amplitude versus frequency (kHz) for Eurostring violin D4 string. (c) Normalized amplitude versus frequency (kHz) for Eurostring violin A4 string. (d) Normalized amplitude versus frequency (kHz) for Eurostring violin E5 string.

qualitative analysis of cellos sound characteristics that result in a dark and less powerful sound, while the violins sound is bright and powerful. In this work Spicato and Eurostring Cellos, and Eurostring and Stradivarius copy violins are studied. The goal is to compare instruments with sound characteristics in a wide range and see if quantitative analysis describes effective sound characteristic differences

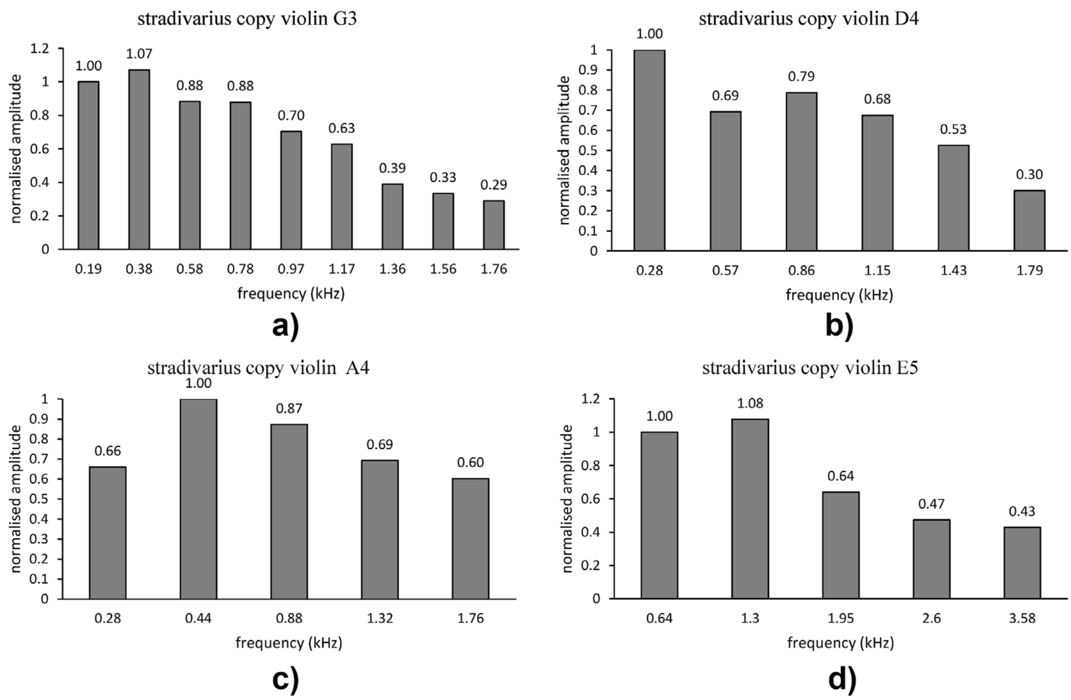

Fig. 11. (a) Normalized amplitude versus frequency (kHz) for Stravidarius copy violin G3 string. (b) Normalized amplitude versus frequency (kHz) for Stravidarius copy violin D4 string. (c) Normalized amplitude versus frequency (kHz) for Stravidarius copy violin A4 string. (d) Normalized amplitude versus frequency (kHz) for Stravidarius copy violin E5 string.

between the cellos and violins. For example, using qualitative descriptors, one violin sounds brighter than another violin. By selecting the cellos and violins, the investigation will reveal whether qualitative differences in sound characteristics can be detected quantitatively because the perception of sound characteristics is highly subjective. Furthermore, instruments of the same string type often have minimal sound characteristic differences.

The focus of this research is to examine the sound characteristic differences between the cellos and the violins. The sound samples used to generate frequency spectra for each instrument represent the most typical sound for the cellos and the violins. Table 10 displays all the descriptors calculated from cellos and violins strings using a Python program. Fig. 12 shows the distribution of f_o and $\bar{f}$ for cello strings C2, G2, D3, and A3, and violin strings G3, D4, A4, and E5. The value of $\bar{f}$ is significantly higher than f_o.

Fig. 13 displays the distribution of affinity values (A), sharpness values (S), harmonicity values (H), monotony values (M), mean affinity (MA) and mean contrast (MC) for cello strings C2, G2, D3, and A3,

Table 10. Descriptors of Spicato and Eurostring cello, and Eurostring and Stradivarius copy violin strings.

String	f_o (kHz)	$\bar{f}$ (kHz)	A	S	H	M	MA	MC
Spicato cello C2	0.06	0.37	5.71	0.14	5.81	−0.05	0.66	0.26
Eurostring cello C2	0.1	0.16	1.56	0.1	1.95	−9.19	0.91	0.21
Spicato cello G2	0.09	0.43	4.49	0.17	6.95	−0.075	2.82	0.39
Eurostring cello G2	0.09	0.55	5.65	0.09	0.94	−1.55	3.355	0.30
Spicato cello D3	0.14	0.49	3.32	0.2	5.42	−0.124	2.02	0.51
Eurostring cello D3	0.14	0.9	4.18	0.1	0.72	−1.55	3.86	0.35
Spicato cello A3	0.22	0.49	2.21	0.3	2.94	−0.28	0.99	0.23
Eurostring cello A3	0.22	1.57	7.12	0.09	12.38	−2.47	3.79	0.31
Eurostring violin G3	0.19	0.74	3.9	0.24	3.04	−0.06	2.35	0.23
Stradivarius violin G3	0.19	0.78	3.99	0.16	0.12	−0.11	2.347	0.37
Eurostring violin D4	0.28	0.81	2.8	0.31	0.45	−0.08	2	0.63
Stradivarius violin D4	0.28	0.86	2.99	0.25	0.11	−0.09	2.22	0.40
Eurostring violin A4	0.43	1.47	3.38	0.23	4.07	−0.11	2.2	0.45
Stradivarius violin A4	0.44	0.88	2	0.26	0.69	−0.13	1.00	0.27
Eurostring violin E5	0.65	1.83	2.81	0.26	0.47	−0.17	1.57	0.53
Stradivarius violin E5	0.65	1.68	2.58	0.27	0.56	−0.20	1.39	0.38

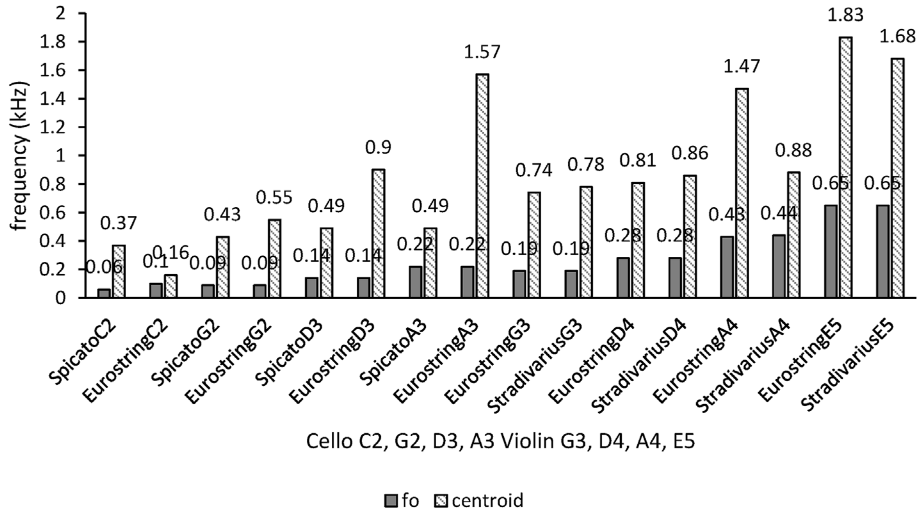

Fig. 12. Distribution of f_o and $\bar{f}$ (kHz) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5.

and violin strings G3, D4, A4, and E5. Affinity (A) explains the spectrum distance, that is, how far f_o is from $\bar{f}$. If f_o and $\bar{f}$ are close, then the sound is considered more affinity with $\bar{f}$, where A has a value close to 1. From Fig. 13a, Eurostring cello string C2 has the highest affinity (having the lowest A value (1.56), approaching 1, indicating that f_o and $\bar{f}$ are close).

Sharpness S represents the variation in amplitude a_o relative to the normalized amplitudes a_{norm} in the spectrum. S is a measure of the perceived relative amplitude a_i from a_o (i.e., a_o in the distribution of a_i). $S = 1$ represents pure sound with a dominant maximum without any high frequencies f_i (only f_o). In actual conditions, S is always less than 1. Spicato cello string A3 and Eurostring violin string D4 have the brightest sound (maximum S value).

Sound is considered more harmonic when f_i is close to an integer multiple of f_o, and less harmonic when f_i is significantly different from an integer multiple of f_o. If all f_i are harmonics of f_o, then $H = 0$. Every time there is one or more f_i that are not harmonics of f_o, H increases. Although D3 is having non-integer multiple of f_o and thus less harmonic where the H values shall be higher but Fig. 13c show that H value of C2 and G2 are greater than D3. This can be explained that the number of f_i in C2 and G2 are higher than D3 which cumulatively contribute to the value of H. Violin strings D4 and E5 are the most harmonic (having the lowest H value, approaching 0). The H values of cello string are greater than all the violin string because the number of partial in the cello string are bigger which cumulatively contribute to the value of H.

Monotony (M) determines the amplitude variation with frequency, assessing the uniformity of the f_i distribution. After f_o, the next maxima, and the subsequent ones, can have increasing or decreasing amplitudes, meaning their amplitudes can increase (increased monotony) or decrease (decreased monotony). Cello string A3 exhibits the greatest amplitude reduction with the greatest decrease in the M value. M indicates whether harmonics exist in most successive decreases (negative M) or in most successive increases (positive M) following f_o. Cello string A3 shows harmonics in most successive decreases (negative M) following f_o.

Clarity or transparency is expressed by Mean Affinity (MA). MA assesses the density of the frequency distribution with respect to the minimum value (including f_o). Low MA values indicate a dense secondary sound distribution close to $\bar{f}$. The MA value of cello string C2 indicates a dense secondary sound distribution close to $\bar{f}$.

Mean Contrast (MC) is a coefficient that measures the normalized amplitude a_i against a_o. The maximum MC value for violin string D4 indicates the high normalized amplitude of its secondary frequencies.

This research links the quantitative analysis of sound characteristics to a quantitative description, allowing for the quantitative description of the sound quality of the cello relative to the violin. According to a study conducted at the Academy of Performing Arts in Prague, words like dark, bright, narrow, and full are among the most suitable terms to describe sound characteristics [Moravec & Stepanek, 2005]. These terms are used as references in this paper to describe sound characteristics based on the quantities obtained for the range and amplitude of frequency spectra. Instruments with a high average high-frequency amplitude are considered

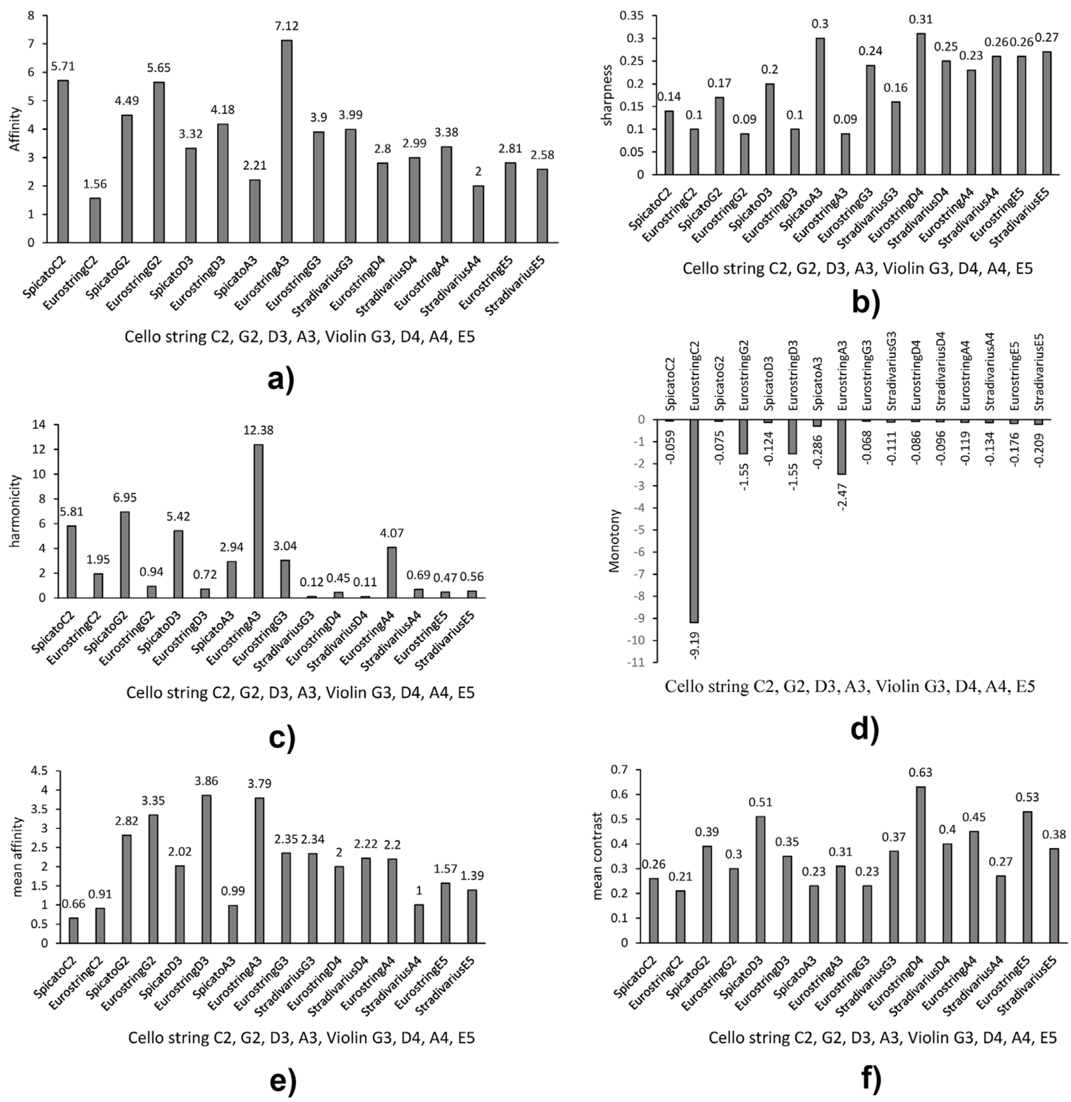

Fig. 13. (a) Distribution of affinity values (A) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5. (b) Distribution of sharpness values (S) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5. (c) Distribution of harmonicity values (H) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5. (d) Distribution of monotony values(M) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5. (e) Distribution of mean affinity values (MA) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5. (f) Distribution of mean contrast values (MC) for Spicato and Eurostring cello strings C2, G2, D3, and A3, and Eurostring and Stradivarius copy violin strings G3, D4, A4, and E5.

bright, while instruments with a low average high-frequency amplitude are considered dark.

Similarly, a large range of harmonic frequencies displayed in harmonic spectra indicates full sound characteristics, while a small range of harmonic frequencies implies narrow sound characteristics. It is important to acknowledge that these terms are highly subjective and can easily be replaced with other descriptors depending on an individual's personal perception of the sound. These terms are used to connect sound quality quantitatively (obtained through spectrum analysis) to acclimatize psychological perceptions in comparing sound characteristics between the cellos and the violins. Fig. 14a represents sound characteristics using the frequency range (from narrow to wide) for cello strings C2, G2, D3, and A3, and violin strings G3, D4, A4, and E5. Fig. 14b represents sound characteristics using the average high-frequency amplitude (from dark to bright) for cello strings C2, G2, D3, and A3, and violin strings G3, D4, A4, and E5. The large range of harmonic frequencies displayed in the harmonic spectra of violin strings indicate full sound characteristics, while the small range of

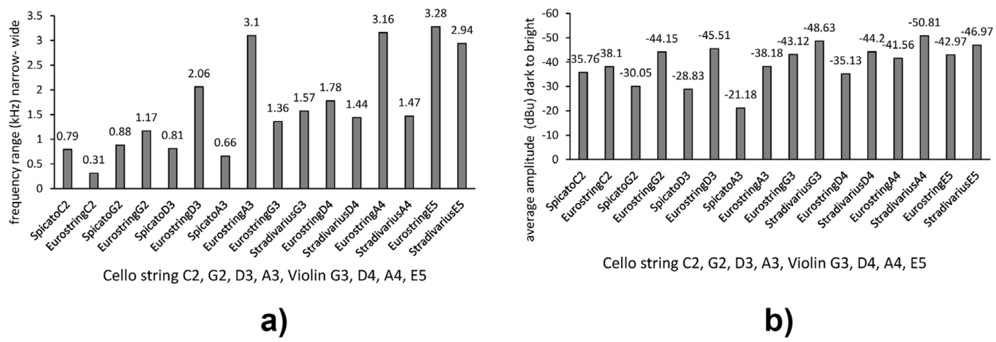

Fig. 14. (a) Sound characteristics using the frequency range (from narrow to wide) for cello strings C2, G2, D3, and A3, and violin strings G3, D4, A4, and E5. (b) Sound characteristics using the average high-frequency amplitude (from dark to bright) for cello strings C2, G2, D3, and A3, and violin strings G3, D4, A4, and E5.

harmonic frequencies displayed in the harmonic spectra of cello strings indicates narrow sound characteristics. All cello strings exhibit a lower average high-frequency amplitude (dark) than violin strings (bright).

In this way, the data collected through FFT software helps create a clear visualization of the sound characteristic differences between the cellos and violins. The violin, with its wide spectral range (from G3 to E5 i.e. 1.36−3.28 kHz) and low average harmonic amplitude, has a full and dark sound characteristic compared to the cello. The bright but narrow sound of the cello, known for its loudness, is reflected in the relatively large average high-frequency amplitude and a low-frequency range (from A3 to G2 i.e. 0.66−0.88 kHz). Fig. 15 is a sound spectrogram that illustrates how the amplitude of a frequency changes over time. In Fig. 15, the wide frequency range is maintained almost throughout the duration. The high frequencies decay relatively quickly for the cello compared to the violin, explaining the narrow sound characteristic and emphasizing the brightness, suggesting a high amplitude at high frequencies.

A relatively large initial frequency range suggests that plucking the strings can contribute to the bright and full sound characteristics during the attack, but it does not persist throughout the entire sound duration. However, the relatively rapid decay of high frequencies suggests that the sound characteristic of the cello is narrower, as implied by the harmonic spectrum. The violin's spectrogram shows clear and consistent frequencies compared to the cello, indicating a sound characteristic with distinct high frequencies. The violin's spectra appear to have the

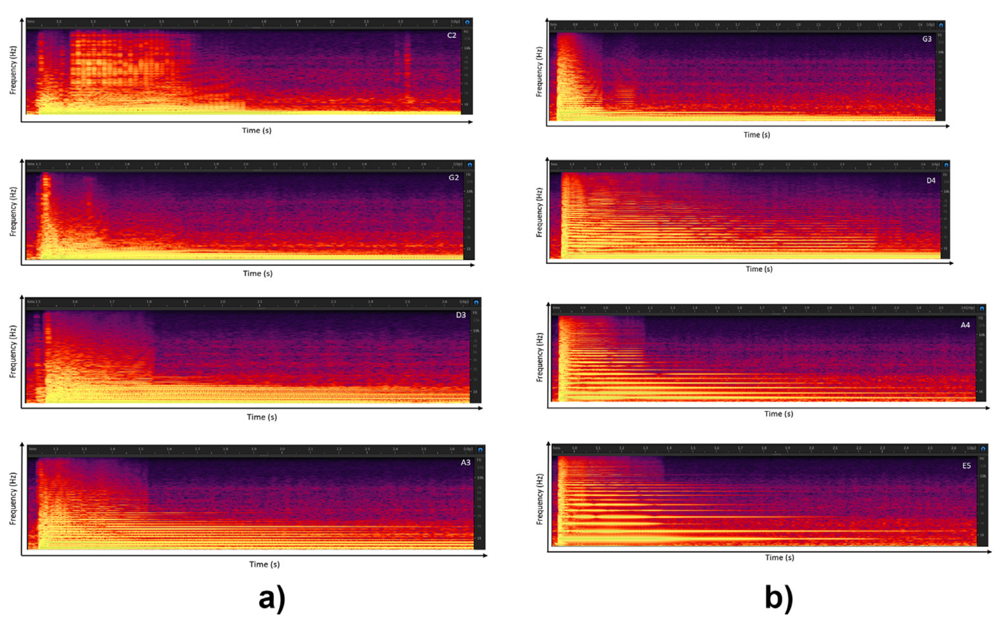

Fig. 15. (a) Time-frequency spectrogram of the sound sample from the Spicato cello. (b) Time-frequency spectrogram of the sound sample from the Eurostring violin.

widest range compared to the cello's harmonic spectrum. By comparing the spectrogram in Fig. 15 with the frequency range graph (Fig. 14a) and average amplitude graph (Fig. 14b) for sound feature classification, we can observe that the combination of both qualitative analysis of the spectrogram (Fig. 15) and quantitative evaluation of the harmonic spectrum (Fig. 14a and b) reveals many sound feature elements. The implications of these findings will be discussed further in the conclusion section.

4. Conclusion

From this research, it can be concluded that spectral analysis is useful for obtaining information that can be used to compare the sound quality characteristics of the cellos and the violins. According to the results, the violin has a wide and bright sound characteristic with a wide frequency range (max 3.28 kHz) and an average intensity ranging (max −50.81dBu) for the first 10 high notes. The cello has a narrow and dark sound quality with a small frequency range (max 3.1 kHz) and an average intensity ranging from (max −45.51dBu) for the first 10 high notes. Sound characteristics for the cellos and violins based on the frequency range and average intensity of the first 10 high notes are useful for measuring how the sound quality characteristics of the cellos and violins relate to each other. The results show that the frequency range in the harmonic spectrum of the violins strings are larger than that of the cellos, suggesting a relatively full sound quality in the violin. This research is limited in several aspects. The most prominent limitation is the subjectivity of sound characteristic perception. Each individual perceives sound differently. This paper takes a more objective approach by attempting to categorize sound characteristics using only the terms "bright" or "dark" as a reference for distinguishing sound characteristics between the cellos and the violins. The cello has a less powerful sound while the violin sound is more powerful because:

1. The affinity (A) from the cello showed that $\bar{f}$ is far from f_o since the high A values showed that it is not close to 1 compared with the cello.
2. The high value of S for violin indicate it approached the pure sound with a dominant maximum without any high frequencies f_i (only f_o) ($S = 1$).
3. The H value for violin approach zero. (If all f_i are harmonics of f_o, then $H = 0$).
4. Cello string A3 exhibits the greatest amplitude reduction with the greatest decrease in the M values.

The perception of sound characteristics is a complex process, and data collected through spectral analysis is insufficient to fully explain the sound characteristics of the cellos and the violins when they are heard. Referring to the method of sound characteristic analysis in this research, there are some improvements that can be made to obtain more accurate and precise results. Determining the average intensity for all existing high notes (not just the first 10 high notes) would provide a more accurate assessment of the "description" of the sound characteristics of each cellos and violins. Quantitative sound characteristic analysis in the form of spectral analysis has many applications in music, science, and technology. By developing methods for quantitative sound characteristic analysis, it can achieve what traditional qualitative sound characteristic analysis cannot. Through quantitative analysis, we can translate the sound quality characteristics (often tied to emotions or feelings) into data that can be understood and analysed by a computer. With the quantitative information contained in sound characteristics, one can convert data to generate alternative sensory outputs while preserving the same emotions and meaning conveyed by those sound quality characteristics.

5. Suggestion for further research

This paper offers quantitative sound characteristic of cellos and violins to show features for representing cellos and violins signals. The quantitative information contained in sound characteristics has been classified based on seven descriptors. Further work will be conducted on different violins classification as tools for selecting a good-sounding violin using the 7 descriptors mention above. For example, one can observe, using qualitative descriptors, that one violin sounds brighter compared to another violin (Hamdan et al., 2021). The investigation will reveal whether qualitative differences in sound characteristics can be detected in quantitative analysis. It is important to note that the perception of sound characteristics is highly subjective. Furthermore, instruments of the same string type often have minimal sound characteristic differences.

Ethics information

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Conflict of interest

No conflict of interest.

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References

Deng, J. D., Simmermacher, C., & Cranefield, S. (2008). A study on feature analysis for musical instrument classification. *IEEE Transactions on Systems, Man, and Cybernetic, Part B (Cybernetics), 38*(2), 429–438, 10.1109/.

Essid, S., Richard, G., & David, B. (2006). Instrument recognition in polyphonic music based on automatic taxonomies. *IEEE Transactions on Audio Speech and Language Processing, 14*(1), 68–80. https://doi.org/10.1109/TSA.2005.860351.

González, Y., & Prati, R. C. (2019). Characterization of the sonority associated with woodwinds instruments through spectral analysis. In *Brazilian symposium on computer music, Brazil*.

Gonzalez, Y., & Prati, R. C. (2021). Applications of FFT for timbral characterization in woodwind instruments. In *18th Brazilian symposium on computer music-BSCM* (pp. 68–73).

Gonzalez, Y., & Prati, R. C. (2022a). Acoustic descriptors for characterization of musical timbre using the Fast Fourier transform. *Electronics, 11*, 1405.

Gonzalez, Y., & Prati, R. C. (2022b). Acoustic analysis of musical timbre of wooden aerophones. *Romanian Journal of Acoustics and Vibration, 19*(2), 134–142.

Gonzalez, Y., & Prati, R. C. (2023). Similarity of musical timbres using FFT-acoustic descriptor analysis and machine learning Eng-Advances. *Eng, 4*, 555–568.

Hamdan, S., Musib, A. F., Sawawi, M., & Othman, S. H. (2021). The frequency spectrum and time frequency analysis of different violins classification as tools for selecting a good-sounding violin. *Wacana Seni Journal of Arts Discourse, 20*, 27–40. https://doi.org/10.21315/ws2021.20.3.

Hamdan, S., Musoddiq, I. A., Musib, A. F., & Sawawi, M. (2020). Time frequency analysis of peking gamelan. *Pertanika Journal of Science and Technology, 28*(2), 441–457.

Herrera-Boyer, P., Klapuri, A., & Davy, M. (2006). Automatic classification of pitched musical instrument sounds. In *Signal processing methods for music transcription* (200, p. 163). Springer.

Herrera-Boyer, P., Peeters, G., & Dubnov, S. (2003). Automatic classification of musical instrument sounds. *Journal of New Music Research, 32*(1), 3–21. https://doi.org/10.1076/jnmr.32.1.3.16798.

Jovanovic, J. (2020). How does Shazam work? Music recognition algorithms, fingerprinting, and processing. *Total*. https://www.toptal.com/algorithms/shazam-it-music-processing-fingerprintingandrecognition. accessed on 1 April 2024.

Klapuri, A., & Davy, M. (2006). *Signal processing methods for music transcription*. Springer.

Lin, C. C., Chen, S. H., Truong, T. K., & Chang, Y. (2005). Audio classification and categorization based on wavelets and support vector machine. *IEEE Transactions on Speech and Audio Processing, 13*(5), 644–651. https://doi.org/10.1109/TSA.2005.851880.

Mallat. (2009). *A wavelet tour of signal processing*. Academic Press.

Moravec, O., & Stepanek, J. (2005). *Verbal descriptions of musical sound timbre and musician's opinion of their usage*. 31st Deutsche Jahrestagung fur Akustik (DAGA), Technischen Universitat Munchen.

Musib, A. F., Hamdan, S., Kipli, K., Sinin, A. E., & Abdullah, J. (2024). *The musical descriptor using AI: Examples in P ramlee songs, accepted by ASEAN Journal on science and technology for development*.

Plomp, R. (1976). *Aspects of tone sensation*. Academic Press.