Archives of Acoustics Vol. 49, No. 1, pp. 11–18 (2024), doi: 10.24425/aoa.2024.148774

Research Paper

The Influence of Violin Tailpiece Material on Acoustic Properties of a Violin

Adam ŁAPIŃSKI[(1)], Ewa SKRODZKA[(2)*], Andrzej WICHER[(2)]

[(1)] *The Ignacy Jan Paderewski Academy of Music in Poznań*
Poznań, Poland; e-mail: adam.lapinski113@gmail.com

[(2)] *Department of Acoustics, Faculty of Physics*
Adam Mickiewicz University
Poznań, Poland; e-mail: awaku@amu.edu.pl

*Corresponding Author e-mail: afa@amu.edu.pl

(*received July 25, 2023; accepted October 22, 2023; published online January 18, 2024*)

The different mechanical properties of the materials from which the tailpieces are made have a noticeable effect on the acoustic performance of the violin. These elements are made today from ebony, rosewood, boxwood, aluminium, or plastic. The aim of this study was to check the exact impact of tailpieces made of different materials on the frequency response function (FRF) of a violin's bridge and the timbre of the instrument's sound. For this purpose, the bridge FRF measurement was carried out, and a psychoacoustic test was conducted. The material from which the tailpiece is made to the greatest extent affects the modal frequencies in the range 530–610 Hz (mode B1+), which mainly manifested itself in a change in the instrument's timbre in terms of the brightness factor. The study showed that the lighter the tailpiece, the darker the sound of the violin. It was also revealed that the selection of accessories affects factors such as openness, thickness, and overall quality of the sound.

Keywords: tailpiece; violin; acoustical properties; exotic materials; violin-making; luthiery.

1. Introduction

Violin-making is an extraordinary art form that passionately combines artistic freedom with scientific objectivity. The mathematical complexity that prevents a comprehensive definition in terms of acoustics, the beauty of the harmonious form, and the appeal of each curve and line make the violin more than just a musical instrument. Even though for years, physicists, acousticians, and luthiers have been trying to explain the relationship between the physical parameters of a violin and the timbre of its sound (Hutchins, 1983; Skrodzka *et al.*, 2013; 2014), there is still a vast number of unexplored variables whose influence on the sound is unknown. One such variable is the tailpiece, a small plate used to attach the strings to the instrument. Its appearance has undergone constant changes throughout the evolution of the violin. Today, these pieces are made from the wood of dense hardwoods such as ebony, rosewood, and boxwood (Bucur, 2016). However, in the 17th century, due to the difficult availability of exotic materials, violin accessories were made from more common woods, such as sycamore (Pollens, 2009). Tailpieces made of this material were often decorated with numerous ornaments, sometimes with intricate marquetry or intarsia. Having different shapes and dimensions, they were an element that gave the instrument its individual and unique character (Houssay, 2014). Unfortunately, the 19th century industrial revolution standardised the appearance of violin accessories. In the manufactories and factories, there was no time for individual attention to each instrument and no room for woodcarving show-offs when making tailpieces. In the 20th century, with the development of new synthetic materials, plastic, aluminium, and graphite composite also began to be used.

There have been many attempts to explain the influence of a tailpiece on a violin sound (Fouilhé *et al.*, 2009; 2010; Leung, 2016). In order to objectively present the acoustic properties of tailpiece vibration, an experimental modal analysis was carried out by Stough (1996). He outlined five tailpiece modes, which were divided into two groups based on the nature of the vibration: three swing modes and two rotation modes (see Table 1). It was also noted that their frequency is influenced by the tailpiece's weight and the length of the tailgut. The topic was later revisited by Borman and Stoppani (nd), who made and published visual representations of the tailpiece's modal vibrations on his website (Stoppani *et al.*, nd). The available animations clearly explain the nature of the dynamics and movement of each violin element at a specific frequency.

Comparing Tables 1 and 2, it can be seen that, some frequency modes of the tailpiece overlap with some of the modal frequencies of the plates. This phenomenon has preoccupied scientists for years. Both Hutchins (1993) and Fouilhé *at al.* (2011), noted that matching the tailpiece's horizontal rotation mode (Rh) and vertical rotation mode (Rv) modal frequencies to the instrument's air modes can noticeably affect the violin's tone and timbre. Fouilhé also points out that matching the tailpiece's main resonance to a frequency he calls "the body's wolf resonance" allows wolf suppression. Wolves are a significant issue, particularly for cello players. Thus, many luthiers experiment with the parameters of the tailpiece to weaken them or change the frequency at which they occur (Zhang, Woodhouse, 2018; Gourc *et al.*, 2022).

Table 1. Modes of a tailpiece identified by Stough (1996). Frequency and quality factor (Q) are shown in ranges because their exact values depend on individual tailpiece parameters.

Mode	Full name	Frequency [Hz]	Q
Sb	Swing bass side mode	100–140	50–80
St	Swing treble side mode	120–160	60–80
Su	Swing under mode	180–230	35–70
Rh	Rotation mode, horizontal axis	300–800	34–110
Rv	Rotation mode, vertical axis	300–800	38–110

Table 2. Violin modes observed by Stoppani *et al.* (nd). Frequency and quality factor (Q) are shown as the average of two measurement sessions.

Mode	Full name	Frequency [Hz]	Q
A0	Fundamental air resonance	283	33.5
CBR	Centre bout romboid	416	50.3
A1	Second air resonance	470	54.0
B1–	First breathing mode	494	50.5
B1+	Second breathing mode	588	38.4

Nowadays, as shown in Fig. 1, there are three main styles that tailpieces are made in: English (Hill), which has a pointed shape similar to a house's roof; French, which has an elegant, rounded shape; and

Fig. 1. Different types of tailpiece shapes described by Folland (2010).

"tulip", which calls to mind a wine glass or a tulip. However, according to Folland (2010), the shape does not significantly affect the sound. On the other hand, it turns out that the tailpiece's position relative to the bridge can make a huge difference in sound timbre. Modern luthiers pay particular attention to the length of the string between the bridge and the tailpiece nut while installing a new tailpiece. This distance is called the after-length of the string. In a violin, it should be about 54.5 mm long (1/6 of the length of the vibrating string). By shortening or lengthening the tail gut, the after-length can be modified, and different sound effects can be achieved. According to Fouilhé and Houssay (2013), the shortening of the tail gut stiffened the cello tailpiece, resulting in a more powerful, harmonically richer, yet more demanding in emission sound. While the maximum extension of the tail gut resulted in a milder, less powerful, aggressive sound and diminution of the wolf note appearance. Adjusting the after-length by changing the length of the tailpiece did not noticeably affect the sound.

Another critical factor that can affect the overall sound of a violin is the material from which the tailpiece is made. In everyday use are those made of rosewood, boxwood, ebony, plastic, or metal. The physical properties of these materials differ considerably. It is difficult to imagine that the significant differences in density, the modulus of elasticity, and the damping coefficient of these materials do not affect the natural frequencies of the tailpiece and the sound of the entire instrument. Much research has been devoted to the wood used in the construction of violin plates (Mania *et al.*, 2015; 2017). Both scientists and luthiers pay a lot of attention to the properties of the material used in this process. It is difficult, however, to find information in the literature that does not deal with spruce and maple, the woods most commonly used to make instruments. The influence of ebony fingerboards or tailpieces made of exotic materials has not yet been well described. To the best of the authors' knowledge, no studies have yet been conducted to answer questions about the tailpiece material's effect on the violin's acoustic properties. The aim of this work is to find the answer to the question if there are any audible differences between violin timbre with different tailpieces attached and if the material of a tailpiece can affect the bridge FRF measurement and instrument sound.

2. Material and the method of bridge FRF measurements with different tailpieces attached

In order to objectively illustrate how the vibrations of tailpieces made of various materials affect the sound, the FRFs of the violin's bridge were measured. The bridge was hammered at a treble side in a direction perpendicular to the fingerboard, mimicking the excitation of the strings by the bow, while the response signal was measured with the accelerometer placed on the rear side of the bridge near the top left corner, with a measuring axis pointing towards the tailpiece (Fig. 3). As in (Fouilhé *et al.*, 2011; Fouilhé, Houssay, 2013) the measured function was accelerance (a/f). At this point, it should be noted that the acceleration function is not a standard in bridge dynamic measurements. The literature is richer in measurements of bridges mobility (v/f) as in (Jansson 1997; 2004), which can be executed by aligning the excitation axis parallel to the measurement axis. It is also worth noting that in several cases, the accelerometer or excitation point is placed in locations other than the side of the bridge, which leads to the measurement of different characteristics, for instance: (Boutin, Besnainou, 2008) or (Alonso Moral, Jansson, 1982).

According to (Minnaert, Vlam, 1937), the movements of the violin bridge during playing can be divided into: a) vibrations in the plane of the bridge, b) bending vibrations perpendicular to this plane, and c) torsional vibrations, also perpendicular to this plane (Fig. 2). Fouilhé *et al.* (2011) also indicate that modes 1, 2, and 4 of the tailpiece were found to be the most important. As could be seen in the visual representations from Stopanni's *et al.* website (nd) second and fourth modes of the tailpiece exhibit a pronounced

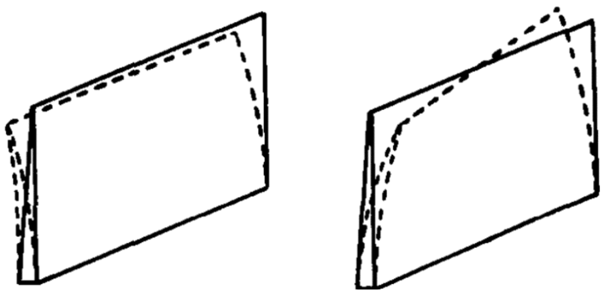

Fig. 2. Schematic representation of "flexural" (left) and "torsional" (right) deformation of the bridge (Minnaert, Vlam, 1937).

vertical movement, which could affect the forward and backward displacement motion of the bridge. Let us assume that, the accelerometer was intentionally placed on the axis of this motion, perpendicular to the axis of excitation.

Five tailpieces, made of ebony, rosewood, boxwood, plastic (Wittner), and aluminium (Otto Infeld), were investigated (Fig. 3). Wooden ones were shaped in a "tulip" style. Their geometric parameters and weight are listed in Tables 3 and 4. Tailpieces made of wood had two attachable fine tuners on A and E string, although the plastic and aluminium ones had four built-in fine tuners. All of them were attached with a nylon tailgut to two instruments, which is further labelled as instrument A – based on the model of A. Stradivari – "Leonora Jackson" and instrument B – on the model of A. Stradivari "Dancla". Professional violin-makers made both instruments. In terms of the

Fig. 3. Tailpieces used in the study – from left: ebony, rosewood, boxwood, plastic, aluminium.

Table 3. Geometric parameters of the tested tailpieces.

Material	After-length [mm]		Length of a tailpiece [mm]
Instrument A and B	Instrument A	Instrument B	Instrument A and B
Ebony	55.0	54.0	111
Rosewood	54.5	54.5	114
Boxwood	54.0	54.0	112
Plastic	54.5	54.0	108
Aluminium	55.0	51.0	115

Table 4. Mass of the tested tailpieces.

Material	Tailpiece mass [g]	Fine tuner mass [g]	Tail gut mass [g]	Total [g]
Ebony	15.8	5.2 × 2	1.2	27.4
Rosewood	14.5	5.2 × 2	1.2	26.1
Boxwood	11.0	5.2 × 2	1.2	22.6
Plastic	19.3*		1.2	20.5
Aluminium	38.8*		1.2	40.0

* The tailpiece has four built-in fine tuners.

Table 5. Strings attached to the tested instruments.

	String G	String D	String A	String E
Instrument A	Evah Pirazzi Gold	Evah Pirazzi Gold	Chromcor	Evah Pirazzi Gold
Instrument B	Evah Pirazzi	Evah Pirazzi	Chromcor	Evah Pirazzi

material, model, arching, varnish, and strings, they were similar to each other. The violin plates, measuring 15.5 mm in height, were crafted using wood of the finest quality. Notably, material in both instruments exhibits exceptional properties, with spruce possessing a density lower than 0.35 g/cm^3 and a soundwave propagation velocity surpassing 5850 m/s, while maple demonstrates a density lower than 0.56 g/cm^3 and a soundwave propagation velocity greater than 5100 m/s, which according to (Bucur, 2006), is noticeably better than the usual wood used in violinmaking. The instruments were covered with spirit varnish and set up with Pirastro brand strings (Table 5). The only significant difference was the year of manufacture. Before the experiment, instrument B had been in use for two years, while instrument A had only been played for about a month.

The experimental tool used was an experimental modal analysis with a fixed response point and varied excitation point. The response signal was measured by the Ono Sokki accelerometer NP-2110, of 0.6 g in mass, attached with bee wax. The bridge was excited by an impact hammer with a piezoelectric force transducer (PCB Piezoelectronics Impact Hammer Model 086C05) (Fig. 4). The accelerometer and impact hammer were connected to the ONO SOKKI analyzer CF 5210. The modal parameters were calculated using the software packet SMS STAR Modal. Measurements were made for the frequencies 10–1600 Hz with a spectral resolution of 2 Hz. Ten spectral averages were used to improve the signal-to-noise ratio. Each measurement was controlled by the coherence function. The measured and analyzed function was the frequency response function module, similar to our previous works (Mania *et al.*, 2015; 2017; Mania, Skrodzka, 2020). After each tailpiece change, the violins were tuned.

Fig. 4. Position of the accelerometer and the impact hammer in the modal experiment.

Every effort has been made to ensure that the afterlength is 54.5 mm ±0.5 mm (Table 3). To prevent any influence from the vibrating strings on the experimental results, a cloth was carefully inserted between the strings and the fingerboard near the upper nut.

3. Measurement results and discussion

3.1. Instrument A

In Fig. 5, parts of FRFs registered for the instrument A are shown in frequency ranges of 240–300, 400–460, 460–520, and 540–600 Hz. The frequency ranges were selected so that each potentially contains one or two violin signature modes (Table 2).

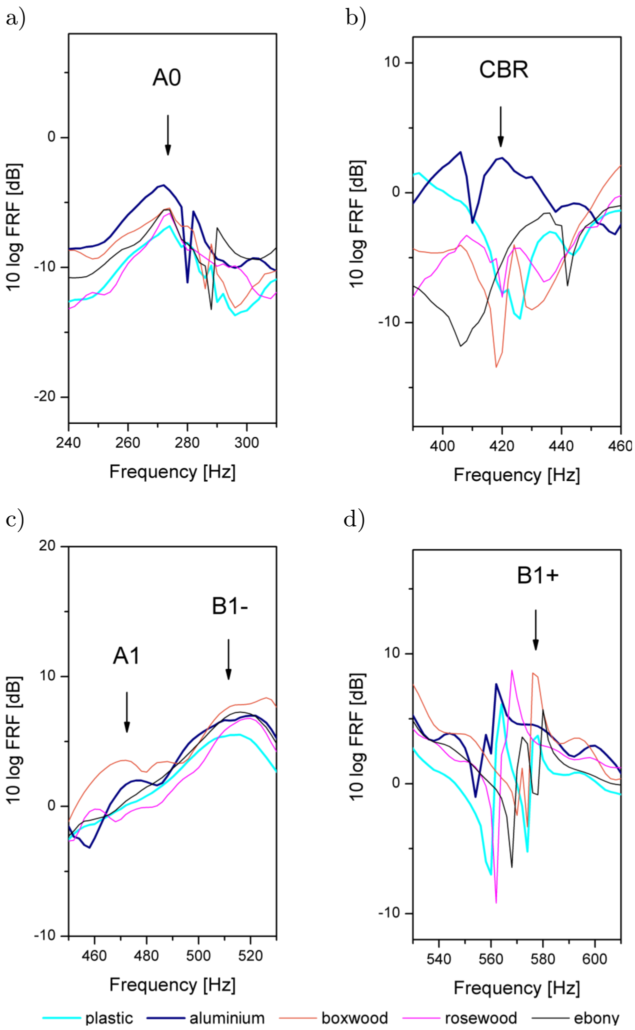

Fig. 5. FRFs for the instrument A in the range of:
a) 240–320 Hz mode A0; b) 380–460 Hz – mode CBR;
c) 450–530 Hz – modes A1 and B1−;
d) 530–610 Hz – mode B1+.

The most significant influence of the tailpiece material on the bridge FRF can be observed around modes A0 and B1+. In Fig. 5a, it can be seen that the highest FRF value for the A0 mode was observed for the aluminium tailpiece and the lowest for the plastic one. Although the frequency at which this mode occurs remained constant, the distinct peak around 285 Hz, which varied depending on the tailpiece used, is worth noting. A more significant effect of the tailpiece material can be observed in the frequency range of 530–610 Hz. From Fig. 5d, it can be deduced that the frequency of the maximum of the B1+ mode can be split, increased or decreased (Table 6). The lowest frequency of this mode was observed for the aluminium tailpiece and the highest for ebony one. It is difficult to interpret the effect of tailpiece material on the bridge FRF in the 400–530 Hz frequency range (Figs. 5b–c).

3.2. Instrument B

Figure 6 shows parts of the instrument B's bridge FRF divided into four frequency ranges, the same as for the instrument A. From Fig. 6a it can be derived that the frequency of A0 can be increased or decreased within a range of several Hertz depending on the tailpiece used. In the range of 440–530 Hz (Figs. 6b–c), it is noticeable that wooden tailpieces have a lower FRF value than those made of plastic or metal. Also worth highlighting is the characteristic minimum visible only for the aluminium tailpiece at 423 Hz in the direct vicinity of the CBR mode. From Fig. 6d, the B1+ mode is visible, which maximum was split for aluminium, plastic, and rosewood tailpieces. The frequency of this mode was lowest for the aluminium one and greatest for that made of rosewood. Depending on the tailpiece used, the frequency of the B1+ mode can be adjusted in the 12 Hz range.

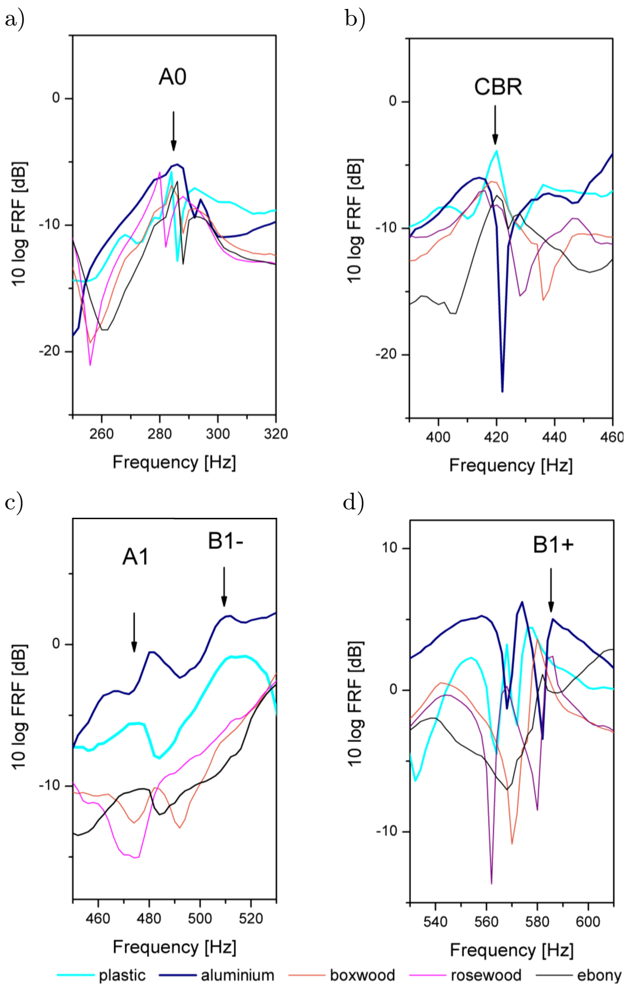

Fig. 6. FRFs for the instrument B in the range of: a) 240–320 Hz mode A0; b) 380–460 Hz – mode CBR; c) 450–530 Hz – modes A1 and B1−; d) 530–610 Hz – mode B1+.

3.3. Instruments A and B in a wide frequency range

Bridge FRFs registered for both instruments A and B are shown in Fig. 7 over a wide frequency range of 100–1000 Hz. It may be noted that the bridge FRF of instrument A slightly differs from that of instrument B. Despite these discrepancies, regularity can be observed in the form of similar effects of the individual tailpieces that appear in both instruments. The shapes of the bridge FRF graphs for ebony, rosewood and boxwood tailpieces are similar across the entire spectrum depicted in Fig. 7. Furthermore, tailpieces made of aluminium or plastic have higher FRF values up to 600 Hz than wooden ones. Also worth mentioning is the frequency range between the A0 and CBR modes – 320–400 Hz. It notes high FRF values for the plastic and metal tailpieces and a clear maximum around 380 Hz. It is also important to note the peak below 180 Hz for the plastic one, which repeats for both instruments A and B but is absent for the other tailpieces.

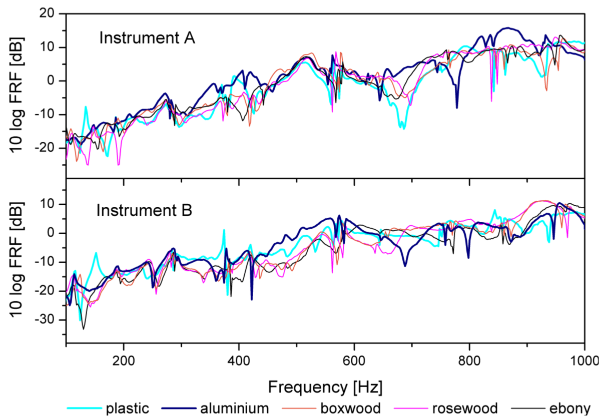

Fig. 7. FRFs showing amplitude changes for instrument A and B in a wide frequency range of 100–1000 Hz.

3.4. Interim summary

As seen from Figs. 5–7, the tailpiece material really has an impact on the frequencies of the bridge FRF.

Table 6. Modal frequency B1+ [Hz] for the material from which the tailpiece is built.

	Plastic	Aluminium	Boxwood	Rosewood	Ebony
Instrument A	564*	562	576	567	580*
Instrument B	576*	574*	580	586*	582

* Maximum clearly splits.

It affects frequencies in the 530–610 Hz range the most. In the case of the aluminium tailpiece, the frequency of B1+ mode has the smallest value of FRF in both instruments A and B. The modal frequency of the ebony tailpiece relative to the metal one was greater by an average of 13 Hz, while that of the rosewood was greater by 9 Hz, that made of the boxwood by 10 Hz, and that of the plastic by 2 Hz (Table 6). The frequency differences shown in Table 6 are generally greater than the measurement error, but they may not be solely due to the tailpiece replacement, and may be caused by some degree of tailpiece manipulation, which is unavoidable in this type of experiment. As reported by Torres *et al.* (2020) even after a very serious interference in the violin (removing the top plate and replacing it with another plate and after removing the top plate, drilling holes through the blocks of the soundbox, and then regluing the top) changes in mobility measured at both stages were of the same order of magnitude compared with the initial stage. In our case, the modification of the instrument was not so deep. It can therefore be assumed that our modifications consisting in replacing the tailpiece made a small, consistent, repeatable contribution to the results of the modal experiment. In addition, the replacement of some violin components, including the tailpiece, is a normal procedure for servicing the instrument. In both instruments, the plastic tailpiece caused the maximum of this mod to split. On the broadband spectrum graph, Fig. 7, it is hard not to notice the characteristic peak around 150 Hz for plastic, and around 380 Hz for plastic and metal tailpieces. It is also worth noting that non-wooden ones have generally high amplitude values of FRF below 600 Hz.

4. Results of subjective assessment of violin timbre with different tailpieces attached

Young musicians who attend music schools hone their aural skills in ear training classes. Development in this area is essential for the efficient and mindful performance of music. Scientists agree that sensitivity to differences in sound timbre differs between people who have never had much to do with music and professional musicians who do it professionally (Loebach *et al.*, 2010). From the point of view of neuroscience, along with learning how to play an instrument, numerous changes occur in the cerebral cortex, including areas related to motor coordination, memory, or feeling emotions (King, Nelken, 2009). The brain's ability to remodel neural connections, called neuroplasticity, is responsible for this phenomenon. According to researchers, auditory training leads to transformations in sound perception. Therefore, in order to describe as accurately and reliably as possible the changes in the timbre of instruments with attached tailpieces made of different materials, research has been conducted on a group of 40 qualified musicians and luthiers at the student and professional levels. The group included 13 violinists, 3 violists, 4 cellists, 1 double bass player, 12 luthiers, and 7 musicians who do not play any stringed instrument.

4.1. Method

The 10 recordings of an excerpt from Tchaikovsky's Violin Concerto in D Major, Op. 35 were recorded under concert conditions (in a large hall). Each of them was conducted under the same conditions. Only the tailpiece used was changed. The study used the same two instruments and the same five tailpieces used in the experiment described in Sec. 2 of the paper. The recordings were made using an Audio Technica AT2035 condenser microphone, which was at a distance of about 1.5 meters from a professional violinist. An anonymous test was then conducted on a 40-person study group. Respondents were asked to rate the recordings on a scale of 1 to 5 in terms of brightness, openness, thickness, and overall quality. For example, a "1" indicated that the excerpt was the brightest among the others, a "5" the darkest, and "3" that it was moderate. Respondents were required to point out extreme recordings and rate at least one tailpiece as a "1" and the other as a "5".

The study was conducted on one person at a time and under the same conditions. Silence and professional monitor headphones (Beyerdynamic DT990 PRO) were provided. Each respondent had unlimited time to respond and was free to compare portions of the recording, which were synchronized in a digital audio workstation software. A single survey lasted between 20 and 50 minutes.

4.2. Results and discussion of the survey

Statistical analysis of the survey responses was performed for each of the four rating categories, i.e., brightness, openness, thickness, and overall quality. The factors in the analysis were: instrument (A, B), subject (1–40), material (plastic, aluminium, boxwood, rosewood, ebony). A significance level of $p = 0.05$ was assumed.

The results of the statistical analysis showed that for each rating category, both subject and instrument were not significantly statistical factors. For the dark/bright evaluation, material was found to be the statistically significant factor $F(4,394) = 4.55$ for $p = 0.02$. A post-hoc test (Tukey) showed that there were statistically significant differences in evaluation between metal and boxwood, ebony and plastic, metal and plastic, and rosewood and plastic. The lowest mean score was obtained for metal, the highest for plastic (Fig. 8).

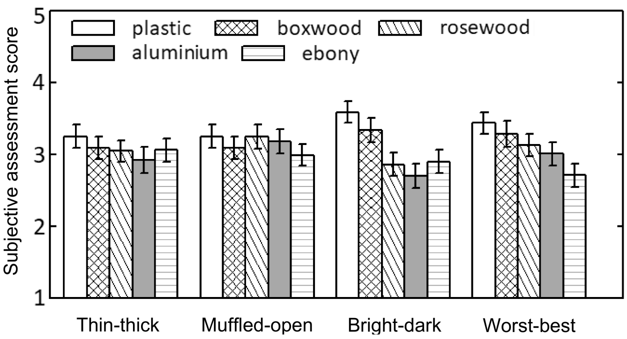

Fig. 8. Average survey scores, with standard errors indicated, for each material type in the four rating categories.

For the overall best/worst rating, the material was again found to be a significant factor $F(4,394) = 3.166$ for $p = 0.014$. Post hoc tests showed that a significantly statistical difference occurred between ebony and plastic. Ebony was found to be the worst material, while plastic was found to be the best. According to most participants, the survey was challenging and required a lot of concentration. The differences between the recordings were noticeable but very subtle. The complicated nature of violin performance was also an issue. It is difficult to perform the same one-minute piece of music identically 10 times. The sound of a violin depends enormously on how the bow is guided along the string and the pressure of the fingers of the left hand. An additional complication was the fact that the instrument's timbre varied from string to string. In addition, it is important to remember that abstract concepts, such as the thickness or darkness of sound, are interpreted differently by different people.

5. Conclusions

We conclude that:

– a tailpiece that is properly matched to a specific instrument can improve its sound;

– the lighter the tailpiece, the darker the sound of the violin and vice versa;

– sound of a violin with plastic or boxwood tailpieces over one with the ebony tailpiece was generally preferred.

Acknowledgments

The authors would like to thank the Ignacy Jan Paderewski Academy of Music in Poznań for providing the apparatus needed for the study. Many thanks also to prof. Andrzej Łapiński for his help editing this article, his good word, and his daily support.

References

1. Alonso Moral J., Jansson E.V. (1982), *Input admittance, eigenmodes and quality of violins*, Report STL-QPSR, www.speech.kth.se/prod/publications/files/qpsr/1982/1982_23_2-3_060-075.pdf (access: 3.08.2023).
2. Borman T., Stoppani G. (nd), *Modal Animations. Borman Violins*, www.bormanviolins.com/modalanalysis.html (access: 8.01.2023).
3. Boutin H., Besnainou C. (2008), Physical parameters of the violin bridge changed by active control, *Acoustics'08*, Paris.
4. Bucur V. (2006), *Acoustics of Wood*, 2nd ed., Springer Berlin, Heidelberg.
5. Bucur V. (2016), *Handbook of Materials for String Musical Instruments*, Springer Cham.
6. Folland D. (2010), *How Tailpiece Can Affect Sound and Playablility. David Folland Violins*, www.follandviolins.com/articles/tailpiece/ (access: 8.01.2023).
7. Fouilhé E., Goli G., Houssay A., Stoppani G. (2009), *Preliminary Study on the Vibrational Behaviour of Tailpieces in Stringed Instruments – COSTIE0601 STSM Results*, www.researchgate.net/publication/267560695_Preliminary_study_on_the_vibrational_behaviour_of_tailpieces_in_stringed_instruments_-_COSTIE0601_STSM_results (access: 8.01.2023).
8. Fouilhé E., Goli G., Houssay A., Stoppani G. (2010), The cello tailpiece: How it affects the sound and response of the instrument, *Proceedings of the Second Vienna Talk*, pp. 63–67.
9. Fouilhé E., Goli G., Houssay A., Stoppani G. (2011), Vibration modes of the cello tailpiece, *Archives of Acoustics*, **36**(4): 713–726, doi: 10.2478/v10168-011-0048-2.
10. Fouilhé E., Houssay A. (2013), String "after-length" and the cello tailpiece: Acoustics and perception, [in:] *Proceedings of the Stockholm Music Acoustics Conference 2013, SMAC 2013*, pp. 60–65.
11. Gourc E., Vergez C., Mattei P.-O., Missoum S. (2022), Nonlinear dynamics of the wolf tone production, *Journal of Sound and Vibration*, **516**: 116463, doi: 10.1016/j.jsv.2021.116463.
12. Houssay A. (2014), The string "after-length" of the cello tailpiece: History, acoustics and performance techniques, [in:] *Proceedings of the International Symposium on Musical Acoustics*, pp. 207–213.
13. Hutchins C.M. (1983), A history of violin research, *The Journal of the Acoustical Society of America*, **73**(5): 1421–1440, doi: 10.1121/1.389430.

14. Hutchins C.M. (1993), The effect of relating the tailpiece frequency to that of other violin modes, *Catgut Acoustical Society Journal*, **2**(3): 5–8.

15. Jansson E.V. (1997), Admittance measurements of 25 high quality violins, *Acustica – Acta Acustica*, **83**: 337–341.

16. Jansson E.V. (2004), Violin frequency response – bridge mobility and bridge feet distance, *Applied Acoustics*, **65**: 1197–1205, doi: 10.1016/j.apacoust.2004.04.007.

17. King A., Nelken I. (2009), Unraveling the principles of auditory cortical processing: can we learn from the visual system?, *Nature Neuroscience*, **12**: 698–701, doi: 10.1038/nn.2308.

18. Leung J. (2016), *Resonant effects of the violin tailpiece*, Msc. Thesis, McGill University.

19. Loebach J.L., Conway C.M., Pisoni D.B. (2010), Audition: cognitive influences, [in:] *Encyclopedia of Perception*, Goldstein B. [Ed.], pp. 138–141, SAGE Publications, Inc.

20. Mania P., Fabisiak E., Skrodzka E. (2015), Differences in the modal and structural parameters of resonance and non-resonance wood of spruce (Picea abies L.), *Acta Physica Polonica A*, **127**(1): 110–113, doi: 10.12693/APhysPolA.127.110.

21. Mania P., Fabisiak E., Skrodzka E. (2017), Investigation of modal behaviour of resonance spruce wood samples (Picea abies L.), *Archives of Acoustics*, **42**(1): 23–28, doi: 10.1515/aoa-2017-0003.

22. Mania P., Skrodzka E. (2020), Modal parameters of resonant spruce wood (Picea abies L.) after thermal treatment, *Journal of King Saud University – Science*, **32**(1): 1152–1156, doi: 10.1016/j.jksus.2019.11.007.

23. Minnaert M.G.J., Vlam C.C. (1937), The vibrations of the violin bridge, Physica, **4**(5): 361–372, doi: 10.1016/S0031-8914(37)80138-X.

24. Pollens S. (2009), Some misconceptions about the Baroque violin, *Performance Practice Review*, **14**(1): 6, doi: 10.5642/perfpr.200914.01.06.

25. Skrodzka E., Linde B.B.J, Krupa A. (2014), Effect of bass bar tension on modal parameters of violin's top plate, *Archives of Acoustics*, **39**(1): 145–149, doi: 10.2478/aoa-2014-0015.

26. Skrodzka E.B., Linde B.B.J., Krupa A. (2013), Modal parameters of two violins with different varnish layers and subjective evaluation of their sound quality, *Archives of Acoustics*, **38**(1): 75–81, doi: 10.2478/aoa-2013-0009.

27. Stoppani G., Zygmuntowicz S., Bissinger G. (nd), *The Signatures Modes*, www.strad3d.org/st_4.html (access: 8.01.2023).

28. Stough B. (1996), The lower violin tailpiece resonances, *Catgut Acoustical Society Journal*, **3**(1): 17–24.

29. Torres J.A., Soto C.A., Torres-Torres D. (2020), Exploring design variations of the Titian Stradivari violin using a finite element model, *The Journal of the Acoustical Society of America*, **148**(3): 1496–1506, doi: 10.1121/10.0001952.

30. Zhang A., Woodhouse J. (2018), Playability of the wolf note of bowed string instruments, *The Journal of the Acoustical Society of America*, **144**(5): 2852–2858, doi: 10.1121/1.5079317.