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ABSTRACT

For centuries, wood, and more specifically spruce, has been the material of choice for violin top plates. Lately, carbon fiber instruments have entered the market. Some studies show that composite materials have potential advantages for making instruments (Damodaran A. et al. (2015)). However, no studies exist that evaluate violins made of different composite materials as judged by listeners. For this study, six prototype violins, differing only by the material of the top plate, were manufactured in a controlled laboratory setting. The six prototype violins were judged by experienced listeners in two double-blind experiments. In contrast to popular opinion that violins made from carbon have or lack a specific sound quality, the study provides insights in the diverse sounds and timbres violins from fiber-reinforced polymers can create. It allows to investigate the links between the perception and the variations in material properties of the soundboards. Additionally, as neither players nor listeners are acquainted with these instruments, these results provide an interesting view on what type of qualities of violin-like sounds are preferred by listeners.

I. INTRODUCTION

The soundboard of a violin has, with few exceptions, always been made out of wood, more specifically of high quality spruce (Picea Abies). However, due to environmental changes and other factors, wood for music instruments is said to be depleting, becomes more expensive, but also lowers in quality[1]. Meanwhile, the increase in use of technical composites such as carbon fiber reinforced polymer (CFRP) and their qualities with regard to moisture stability and durability, has generated research that investigates their material properties and compares them to wood[2-4]. Consequently, in recent years, research has resulted in prototypes and commercially available instruments made from composites[5-9]. However, no comparative studies that assess the sound of composite violins with the same design and setup under controlled conditions is found in literature. Most studies are limited in this regard because the violins to be tested were constructed independently from the research and can therefore vary in a number of attributes unknown to the researcher, like the model, quality of the materials used, construction method or setup[10-14]. In the present study, the influence of the soundboard material is our focus, as a consequence, all other parameters are taken as similar as possible among the tested violins. Under these conditions, we consider the following questions: How do these composite violins sound? Which variations in the construction of the soundboard influence the volume and timbre of the sound? What possible quality factors are more important to the listeners? What possibilities do composite materials offer to expand on the violin's sonic palette as we know it today?

To answer these questions six composite violins were designed and built with top plates from different materials. We ran two experiments with the instruments; the first consisted of an evaluation task with 37 participants, the second of a selection task with 40 participants. In both cases, we examined how experienced listeners judged the timbre of the instruments on a broad spectrum of possible qualities. We examined which instruments were favored, and why, in order to shed light on what sound listeners prefer from such composite violin.

II. CONSTRUCTION OF THE PROTOTYPE VIOLINS

The goal was to build all violins identical except for the top plate, which was made from different materials between the violins. To achieve this goal, all prototype violins were constructed by the same luthier. A carbon fiber reinforced polymer (CFRP) produced by vacuum assisted resin transfer method (VARTM) was chosen as a quick and reliable way to produce the back, sides and neck in one piece in a consistent way (Video[15] showing the production process on a cello). The soundboards were made either from a selection of four composite materials or from spruce, which was added as a reference material (Fig. 1):

1. UDFlax: unidirectional flax fiber reinforced polymer.
2. UDC: unidirectional carbon fiber reinforced polymer.
3. TwillC: laminate of twill woven and unidirectional carbon fiber reinforced polymer.
4. Sandwich: sandwich structure consisting of CFRP skin and an aramid honeycomb core.
5. Spruce: Picea Abies.

The TwillC violin was produced twice (TwillCA and TwillCB) to check the consistency of the influence of the material and production methods on the sound of the violin. Together, these six prototypes give us a variety in material properties like higher damping (UDFlax), different degrees of anisotropy (TwillC & UDC), and a low weight soundboard (Sandwich). The violin with a soundboard from Spruce serves as a benchmark material.

As the used composite materials have a higher longitudinal Young’s modulus than wood, the thickness of the laminate can be decreased in order to have a similar bending stiffness as a spruce plate. The bending stiffness of a plate is thought to be crucial to the sound of a wooden instrument[16], therefore it is taken as a guide to make these novel composite violins. Soundboards of old conventional violins deform most often along the axis of the instrument[17]. Contemporary luthiers therefore aim to make an arching stiff enough to be durable, without making it too stiff, which is thought to be disadvantageous to the sound production of the violin[16]. As composite materials offer a variety in anisotropy, the bending stiffness along the axis of the instrument (D11) was chosen as the primary design criteria. The bending stiffness (or plate rigidities) are derived from the ABD-Matrix of the Classical Laminate Theory. The required thickness for each of these materials was calculated using the eLamX² software package[18]. The composite soundboards were produced by VARTM. More detailed information on the materials, model, and production method are provided in Appendix and[19]. Weight of the soundboards, calculated bending stiffness's D11 (along the axis/longitudinal), D22 (transversal/radial), D66 (shear) and damping of the materials are provided in Table I. The plate rigidities show the variety in anisotropy between the materials. The damping is an approximation derived from the measured Q factor of the first frequency of flat beams which were made in our lab by VARTM (Appx). As this damping value is dependent on the mode measured, the exact value could be misleading. Therefore the damping is given as an approximation in relation to spruce (0), our benchmark material.

The spruce soundboard was carved by a luthier using templates that match the arching of the composite plates. This spruce soundboard was then given a thin clear oil varnish coating. The soundboards were given a simplified sound hole design and were fitted with a conventional spruce bass bar of high quality. The instruments were mounted with a high quality *Aubert* bridge (Savarez ©), spruce soundpost, *Wittner* tailpiece, chinrest, and *fine-tune pegs*® (WITTNER®

GmbH & Co.KG). Strings were *Dominant* for G, D, A (Thomastik-Infeld GmbH ©) and *Kaplan* for E (D'Addario & Company, Inc.©). A second independent luthier was then asked to examine the instruments for any (accidental) differences in the set-up. In this way, a small difference (1 mm) in the placement of the bridge of the UDFlax violin was corrected.

III. THE EVALUATION EXPERIMENT

A. Methodology

Experienced listeners with relevant musical experience were invited to take part in the experiment. The group of participants included (student) instrument makers, musicians, music teachers and composers. Of the 37 listeners, 33 said that they play a music instrument on a regular basis. Their experience ranged from 3 to 52 years of experience with an average of 15.1 years of playing a music instrument. In the weeks before the experiment, potential participants were told that they would have to evaluate on an aural basis seven violins, of which at least one was made of carbon and one made from flax fibers. This information was given to raise interest and recruit a sufficient amount of experienced listeners. As a consequence, some of the recruited listeners were familiar with the research subject (new materials for violins) yet they did not know how many "new" instruments would be used in this test or if there would be one or multiple instruments with a wooden soundboard and/or conventional violins, as a reference.

In the first listening test the members of the audience, rated the six violins individually on a number of attributes. This method was chosen as it is a common way to judge instruments or musicians in competitions, giving the test a high verisimilitude. For each violin, the attributes were presented on a 8-point Likert scale between two opposite adjectives. Most invited participants had Dutch as their mother tongue. As no study that uses Dutch words to describe the sound of violins was available in the literature, a common language had to be defined with the participants. First a list of English words was compiled from scientific literature[11, 20]. Secondly, multiple listeners who would take part in the experiment were asked which words they would like to use for judging violins in Dutch and English as well as how they would translate these words between the two languages. Also the participants were asked how they would like to be questioned. Through this method an expert audience negotiated and agreed on the meaning of pairs of adjectives that could be understood as each other's opposite, with the Dutch translation in brackets: warm (warm) – cold (koud), clear (helder) – dull (dof), loud (luid) – quiet (stil), soft (zacht) – harsh (hard), open (open) – closed (gesloten), good (goed) – bad (slecht), nasal (nasaal) – clear (helder), round (rond) – sharp (scherp), powerful (krachtig) – weak (zwak), rich (rijk) – poor (arm), bright (briljant) – dim (glansloos). Although a unipolar scale is usually recommended in this type of research[20], the participants preferred a bipolar scale.

Participants could fill in the Likert scale for each presented pair of opposite adjectives, or tick a box 'I don't know' (Appx). The listening test took place in a 98-seat concert hall at the Royal Conservatory of Ghent (Mengal, campus Hoogpoort) – School of Arts Ghent. The violin player was a professional musician. Before the experiment, the violin player only tried the instruments on one occasion one month before the experiment. As each instrument would be played at least two times, which resulted in a total experiment time of 41 minutes, the first experiment was performed with one player. Repeating the entire experiment with a second player was found to be less appropriate, given the fact that the listener's task is quite demanding and there is a risk perceptual fatigue influences the results.

First, as requested by the participants, four random instruments (decided by draw) were played (Spruce, UDFlax, TwillCB and Sandwich) to allow the listeners time to get familiar with the acoustics of the hall and the sound of the prototype instruments. The order in which the instruments were presented for the actual experiment was decided by random draw and was: TwillCA(1), TwillCB, Sandwich, UDFlax, TwillCA(2), Spruce, UDC. TwillCA was presented two times unbeknownst to the audience. If TwillCA scores similar both times, this would be a good indication that a difference between violins can be taken as a difference in the sound produced and not a difference in playing or order effect or fatigue.

One after another, with approximately 25-30 seconds in between, each violin was played and the audience was asked to rate the same set of pairs of adjectives for each violin. After the first sequence was completed, the same sequence was repeated. Listeners could indicate their overall preferred, second-preferred and least-preferred instrument, and their preferred instrument regarding warmth, power and richness. For that additional assessment, the audience was given the possibility to hear violins again in pairs of their choice. This resulted in the following additional comparison: TwillCB and UDC; Sandwich and UDFlax; TwillCA(1) and TwillCA(2). It has to be noted that the only violin which was not asked for the additional assessment was the one with a wooden (spruce) top. Additionally, the listeners were asked which adjectives they considered to be most important to judge the sound of a violin. Finally, some details regarding their musical experience were asked as well.

During the entire evaluation experiment, the violinist was positioned on stage approximately 1m behind a lightweight polyester fabric screen. The violin player was blinded with a sleeping mask and the scent of the instruments was covered with a perfume. The instruments were handed to the musician in the predetermined order by a researcher. The lights on stage were dimmed during the test, but left on in the seating area, in order to make sure that the audience could not distinguish the different instruments behind the screen. The violinist played the instruments with her own bow. As in previous studies the bow is regarded in this experiment as an extension of the player's body[12-14]. She played a musical fragment of her own choice (88 seconds) to evaluate the violins, as a musician would normally do when evaluating an instrument. The experiment was recorded for further analysis. The violin player was not questioned during the test, to minimize the time in-between the playing of the instruments. After the test the violin player was asked by the researcher what her favorite instrument was, and if she had any other remarks.

B. Results

First, we examined how the participants described the sound of each violin, based on presented pairs of opposite adjectives. The ratings on each bipolar scale for each violin were compared with a null-hypothesis, using a one-sample t-test with the IBM SPSS® software. The one-sample t-test determines if the population mean is significantly different from a given value or not. This results in a probability value (p-value) providing strong (p-value<0.05) or weak (p-value<0.1) evidence of this deviation from the given value. The null-hypothesis (H_0) was that the audience did not favor one adjective over the other in a pair in order to describe the sound of a violin, which would result in a mean score of 3.5. Strong and weak evidence to reject the null-hypothesis was found for each of the presented violins in a number of cases (Table II). Through this method, adjectives could be objectively linked to the sound of the instruments.

To investigate how reliable these results were, a paired t-test of TwillCA(1) and TwillCA(2) was performed. This test revealed a statistically significant improvement (p-value<0.05) in the rating of TwillCA(2) on four (out of 11) of the bipolar scales powerful – weak (+0.946), loud – quiet (+0.686), bright – dim (+0.829) and good – bad (+0.781) in comparison to the rating of TwillCA(1). This is likely due to the order effect and is discussed in section V.

Fig. 2 shows the rating for two bipolar adjectives: rich – poor and warm – cold. Rich has been shown to be the most important quality for violinists in a previous study[21], while warm is often used to describe the sound of conventional wooden violins in comparison to other materials. TwillCB, UDFlax and UDC show large statistic deviations from the expected mean a random distribution would show towards *warm*. For *rich – poor* only TwillCB and Spruce show a statistically strong deviation towards *rich*. The scale from 2 to 5 was chosen as all our calculated means +/- standard error of the mean (SEM) fit within this scale (Appx).

Fig. 3 shows the selection of ‘best’, ‘second best’ and ‘worst’ instrument overall. TwillCB and UDFlax were mostly chosen as ‘best’ (9). UDC was most often chosen as ‘second best’ (9). Sandwich was chosen most often as ‘worst’ (12).

Listeners were asked which instrument they found “most rich/most powerful/most warm” (Fig. 4). Interestingly TwillCA(2) was preferred more than TwillCA(1), this corresponds with a consistently higher mean score on positive attributes like: *powerful* (+0.95), *bright* (+0.83), *good* (+0.78) and *loud* (+0.69) (Figures Appx). The differences could be explained by the order. TwillCA(1) was the first to be heard, TwillCA(2) came after UDFlax and before Spruce. As UDFlax was never chosen on the question ‘Which instrument did you find most powerful?’, TwillCA(2) may have appeared more powerful in contrast.

Listeners were asked which pair of adjectives they found were “most important to judge the quality of a violin?” (Fig 5). Three of the bipolar pairs were prompted by the previous question “Which instrument did you find most rich/most powerful/most warm”, and so listeners might have a positive bias towards these pairs. *warm – cold* (13) and *rich – poor* (12) scored higher than *powerful – weak* (2). This finding can be interpreted as follows: either these listeners find the power of the sound of a violin secondary to the sound color, or they could have (either intentionally or unintentionally) favored sound color over power in an effort to rate attributes which are thought to be related to wood. The pairs *loud – silent*, *harsh – soft* and *good – bad* were never written down and are therefore not included in Figure 5.

When we examine the Root-Mean-Square (RMS) level of the audio recording made during the evaluation experiment (Fig. 6a) the Sandwich violin stands out with the highest RMS level. RMS level is a measure of the average value of a waveform over time and is an approximation of the acoustic sound level perceived by our ears. The violins with a top plate made from a material with a higher degree of anisotropy: UDC, UDFlax and Spruce have a slightly lower RMS value compared to the other violins. To rule out the effect of the player, additional acoustic radiation measurements of the violins were performed with an impact hammer in a anechoic chamber (Fig. 6b, more info in appendix). These measurements show that the Sandwich violin is the most effective sound radiator between approximately 400 and 4000 Hz. UDFlax is the least effective sound radiator between the measured violins above 400 Hz. Below 400 Hz, the violins with a soundboard made from unidirectional composites, UDC and UDFlax, have the highest average acoustic response.

The violin player's favorite was the Sandwich violin because it was "easy to produce a lot of sound". Her least favorite was UDFlax because she "felt she had to work very hard on the instrument". The violin player had a suspicion that violins 1 and 5 were the same instrument, which was the case (TwillCA).

IV. THE SELECTION EXPERIMENT

A. Methodology

The musician, the acoustics of the hall and the procedure of the evaluation experiment have surely affected the results of our first experiment. Especially a significant order effect was observed in our measurements, which makes the interpretation of the results more difficult and limits the possibility to draw conclusions. Therefore, we conducted a second listening experiment to verify whether similar trends could be observed with a different protocol, based on pairwise comparisons. To limit the fatigue of the listeners, the number of comparisons should not be too large, which reduces the number of instruments that can be used. Three violins from the first experiment were selected: UDFlax, TwillCB and Sandwich. Both UDFlax and TwillCB were preferred in the first experiment, while Sandwich was evaluated most often as “worst” violin.

It is presumable that listeners perceive and judge the sound of a violin in relation to all other presented instruments. As the composite violins sound rather different from conventional violins, one could argue that the listeners’ perception of these violins could be affected if a conventional violin was presented during the same test and that our results would only hold in the particular context of these prototype violins. An additional wooden instrument was therefore added in this experiment. The violin was a Stradivarius model made by the same luthier and was set-up with the same bridge, strings, tailpiece, chinrest and pegs as the other composite instruments. Sound radiation measurements (Fig. 6b) show how this conventional violin has a very different frequency response function from the prototype violins. Considering that one of the main goals of this study is to link the perceptual evaluations of the composite violins to differences in their construction in order to shed light on traditional instruments manufacturing, the conventional violin was thus only used to ensure the relevance of the listeners’ evaluations of these prototype violins when taking into account regular violins as well. Therefore only the pairs comparing two composite violins were analyzed.

In this second experiment, the four violins were presented in pairs to 40 listeners, all members of the Ghent University Orchestra (GUSO). The listeners had an average of 14 years of experience playing music instruments. Fifteen listeners were violin players. The instruments were played behind the same screen as during the first experiment. The selection experiment took place in a 200-seat hall Trechterzaal, Therminal, Ghent University.

The format of the listening test was based on the one used in[14]. The test was conducted twice with a different violin player for each part. The violin players were members of the orchestra. To judge each pair of violins, the musicians first played a scale (34 seconds) on each violin, followed by a short piece of music of their own choice (20-30 seconds) on each violin (Appx). This so-called ABAB format of the experiment made it possible for listeners to hear each violin twice, that is both before and after the other violin[14]. In this way, each musician presented all the violin pairs in ABAB format (Table III). Between the two musicians, the order in which the pairs were presented and which violin went first in a pair was changed over the two tests so the order of presentation was balanced (Appx). In the questionnaire, the listeners were asked which instrument they preferred and why. Listeners could skip a certain pair if they did not have a preference. Secondly, they were given three quality factors: ‘better projection’, ‘better balance’ and ‘better sound color’. They were asked to choose any number of those quality factors that explained why they chose the said violin. If they chose ‘better sound color’, they could further specify their choice using a list of selected adjectives to describe that sound color in more detail. They had the option to add additional remarks to explain their preference. (Questionnaire Appx).

B. Results selection experiment

As a summary of the results shows in Table III, TwillCB was preferred by most of the listeners over UDFlax with both violin players. Listeners clearly favored TwillCB over Sandwich when listening to player 1 but did not in the case of player 2. UDFlax was favored over Sandwich in both cases.

Listeners based their preference mostly on sound color. Only in the case of Sandwich an equal number of listeners gave projection as their reason of preference (Figure in Appendix). As listeners used the adjectives to further specify why they favored the sound color of a certain violin, they ended up with similar choices of adjectives as in the first experiment. UDflax was described most as *warm* and *round,* TwillCB as *clear* and *open,* and Sandwich most as *powerful, bright* and *rich* and least as *warm* (Fig.7). Due to the nature of this test, listeners could only describe the sound of the violin they favored; *harsh*, *sharp* and *nasal* are most often interpreted as negative attributes when used to describe the sound of a violin. This explains why they were not often picked as adjectives to describe the sound color of the favorite instrument. As *nasal* was never picked in our selection experiment, it is not included in the graph.

V. DISCUSSION

In this study, the potential of different composite materials for the soundboards of violins was investigated. Six violin-shaped instruments were built in a controlled setting and investigated in two listening experiments.

The presented results describe the listeners' perspective. In the evaluation and selection experiment we investigated which instruments were preferred and how listeners described their sound. Do some project better than others? Do some have a sound color which is more preferred? What possible quality factors are more important to the listeners?

As expected, our experiments show that by using a variety of composite materials for soundboards of violins, a wide range of sounds and timbres can be produced. As the use of these composite materials allow violin makers to change the sound of a violin in a number of ways, they can offer new artistic opportunities for violin players and composers to explore. Therefore, these findings could have implications for the future development and production of music instruments as well as future musical compositions and performances.

The low ratio of stiffness/density of the flax composite material resulted in a higher weight for the finished soundboard in comparison to the other materials. In the acoustic radiation measurements, UDFlax was the least effective sound radiator between our violins. It is therefore not surprising that the instrument was the least associated with attributes linked to loudness, such as powerful and projection. Our results confirm the theory[22] that a material with a lower ratio of stiffness/density and higher damping is a less efficient sound radiator, resulting in a less powerful or loud sound. Although this instrument was the least favored by our violin player in the evaluation task, it was preferred by many listeners for its warm and round sound color.

The instrument made from a lightweight, low damping and low anisotropy sandwich material consisting of carbon and an aramid honeycomb (Sandwich) was mostly chosen as most powerful, had the highest mean for loud, had the highest RMS value and sound radiation measured and was the only instrument being favored largely for its projection. Yet this instrument was the least preferred in our evaluation task and least picked as favorite in our selection task when played by the first violin player, but was more liked when played by the second player. These findings are in line with a previous study[14] showing that violins with the best projection are not always chosen as favorite by listeners. Listeners' evaluations can be influenced by the performer's way of playing the instrument. In our evaluation experiment, this violin's sound color was described as harsh. This is less clear in our selection experiment, as the nature of this experiment emphasizes the positive qualities of each instrument.

UDC, with a higher anisotropy than TwillCA and TwillCB, was described as round and soft and was chosen less as powerful. This could be an indicator that for composite materials, a higher degree of anisotropy results in an instrument with a round and soft tonal color preferred by many listeners, but with a less powerful sound. This is in line with the simulations performed by Viala[23] that showed variations in anisotropy to have a significant effect on certain modes of the violin. Indeed, the modes for which the radial direction is important will have a lower frequency and more damping when the radial stiffness (Er) is lower (which is the case when the anistropy is high), which intuitively goes well with a less powerful but rounder sound. More research is definitely needed to investigate this aspect and correlate it with numerical predictions.

In our evaluation experiment, two violins were preferred more than others. One had a soundboard from a laminate of unidirectional and woven carbon (TwillCB), the other was made from unidirectional flax (UDFlax). Although UDFlax had the least powerful sound among our prototypes, its sound color being described as warm, soft and round still made it a favorite for many listeners. The other favorite instrument TwillCB had a sound color described as warm and rich. In our selection experiment, TwillCB was favored over UDFlax by the listeners with both players. The listener’s preference in our experiments seem mostly guided by sound color, and less by projection or loudness of the instruments. However, when both instruments have a favorable sound color, the instrument with the better projection was favored between the two most preferred violins. In both experiments, listeners indicated to find a warm sound an important quality parameter, followed by adjectives such as clear, open, round and rich.

When we compare the results from TwillCA to TwillCB, the two instruments with identical top plate materials, it is clear that the instruments were rated differently in our evaluation task. More research is needed to understand what is the cause of these differences. When we examine the scores of TwillCA(1) and TwillCA(2) we observe some differences in attributes that are linked to loudness like powerful or loud. A possible explanation for this finding is that TwillCA(2) was presented after UDFlax, the least powerful and loud instrument. As the listeners had just heard UDFlax, they rated TwillCA(2) in relation to this, resulting in a different score in adjectives related to projection. As TwillCA(1) was the first violin played, it could have been affected by the order in which the instruments were presented. The order effect of the sequence on the rating of violins is not well documented in literature. Research on judge bias in the Idol series shows that in a sequence of seven, the score of the first contestant has the highest negative mean bias[24]. As such, it is feasible that TwillCA(1) was affected by a negative bias due to the order effect.

The instruments presented in this study differ from a classic violin in a number of ways, therefore we cannot directly extrapolate the results from our violin with a spruce soundboard to that of wooden violins in general. We can only say that between our prototypes, the violin with a spruce soundboard was not favored over the full-composite violins and did not stand out in a particular way with regard to tonal color or projection. Future research has to be performed in order to allow for more direct comparisons between instruments with composite top plates and truly conventional, wooden violins. An alternative road future studies could take is to investigate the full-composite instruments as a class of sound-generators of their own, with their own sonic possibilities, and be less concerned about a comparison with their conventional counterparts.

As the experiments presented investigate the sound of these violins from a listener perspective, the perception of these violins by violin players is outside the scope of this study. As the preference of the violin player in our first experiment was the exact opposite of the trend shown by the listeners, it is evident this must be examined further in future experiments. Additionally, examining how these instruments are perceived when they are accompanied by an orchestra or played in an ensemble can provide valuable psychoacoustic insights. Finally, the vibro-acoustical behavior of these violins could be further examined through modal analyses, which would give a deeper understanding on the effect of the material properties on the body shell response of music instruments.

VI. CONCLUSION

Contrary to popular opinion among violin players, there is no specific sound property or quality that we can assign to the material group of fiber reinforced composites. As a consequence no generalizations like ‘the sound of carbon violins lack warmth’ hold in our experiments. Composite materials allow to create violins with a large diversity in sounds and therefore offer possibilities to change the sound to the criteria of the player. In theory, by only varying the material of the soundboard, the sound of a violin could be changed to fit the requirements of the player. Our results follow the logic that soundboards which are more lightweight and have a lower anisotropy are more efficient sound radiators than heavier soundboards with a higher anisotropy. However, the influence of more or less anisotropy on the energy output should be further investigated, as this study only had a limited amount of instruments to compare and draw conclusions from.

Although all our participants can be considered experienced listeners, individuals prefer different violin-like sounds. Depending on which violin player is playing, the preference of the listener can shift between instruments. Although the sound of some violins was favored more than others, there was no such thing as the ‘best’ violin sound overall.

Our results indicate that when violins are played consecutively the order effect is large. Violinmaking or playing competitions, should adapt their methodology accordingly to ensure a fair evaluation of each violin or musician.

This research provides insight in how violins with soundboards from different composites can sound, the possible advantages these materials can offer in relation to the sound they produce as a soundboard for violins, and which of these violins were favored by listeners. However, composite materials offer a great diversity of fibers, polymer matrix and core materials that must still be examined. While the craftsmanship of making good wooden violins has evolved over centuries, resulting in an optimization of the realization of the material's potential. Composite instruments are very new and may require a new kind of craftsmanship in order to obtain optimal results. Composite instruments commercially available today might need more development in order to realize the full potential of these new materials. More research is needed if we wish to discover more regarding both the potential of composite materials for music instruments, and how to realize that potential.

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Appendix

Information about materials and production method of the violins. The composite violin geometry is based on the dimensions of a conventional violin model (Table I), but adapted to facilitate fabrication using a mold. The height of the ribs is 30mm.

Table I: Dimensions of the top plate used for the violin prototypes.

Top plate dimensions	Dimensions (mm)
Length	356
Width upper bout	165
Width center	107
Width lower bout	206

The bodies (back, sides and neck) were made from twill woven mats of carbon fiber reinforced polymer (CFRP) produced by vacuum assisted resin transfer method (VARTM). The carbon fiber used was AKSACA™ A-38, 200 tex (3k) the matrix was EPIKOTE™ Resin MSG™ RIM 135 mixed in a 100:30 weight ratio with EPIKURE™ Curing Agent MGS™ RIMH 137. After VARTM the CFRP was post-cured in a curing oven following the specifications of the manufacturer. After production the quality of the carbon fiber bodies were visually inspected for quality and consistency in the product. Through this method, 3 pieces were eliminated for further use and additional pieces were made.

Table II: Material properties from literature used to calculate the required thickness of the composite soundboards.

Materials	Longitudinal Young's Modulus El (Gpa)	Transverse Young's modulus Et (Gpa)	Density (kg/m³)	Source
Spruce	10 – 14.8	0.36 – 0.73	382 – 495	Spycher M. (2008)
UD Carbon	118.4 – 119.13	8.85 – 10.18	1528.6	Kersemans M. (2014)
UD Flax	26.6 – 29.8	3.31	1330	Phillips S. (2011)
Woven Carbon	62.7 – 68.7	62.7 – 68.7	1540 – 1610	CES Edupack 2019
Aramid Honeycomb	0,0000149	0,0000149	32.5	CES Edupack 2019

Sources:

Spycher M., Schwarze F., Steiger R. (2008) Assessment of resonance wood quality by comparing its physical and histological properties. *Wood Sci Technol* 42:325–342.

Kersemans M., Martens A., Lammens N., Van Den Abeele K., Degrieck J., Zastavnik F., Pyl L., Sol H., Van Paepegem W. (2014) Identification of the Elastic Properties of Isotropic and Orthotropic Thin-Plate Materials with the Pulsed Ultrasonic Polar Scan. *Experimental Mechanics* 54:1121–1132.

Phillips S., Lessard L. (2011) Application of natural fiber composites to musical instrument top plates. *Journal of Composite Materials* 46(2): 145–154.

CES Edupack 2019 19.2.0 (2019) Granta Design Limited, Cambridge, United Kingdom.

As the materials varied in Young's modulus, but needed a similar longitudinal bending stiffness for consistency, the required thickness for each material was calculated based on a thickness pattern usually used in violinmaking. For the spruce top plate this was 3mm at its thickest in the center going towards 2.2mm at the outer edges. This calculation was done using the eLamX² software package that uses the Classical Laminate Theory. Through this method the thickness pattern for spruce was converted into a longitudinal stiffness pattern (D11) that could be used to calculate the required thickness of each composite material. All soundboards were infused (VARTM) using the same epoxy resin as the bodies (See figure 1). Parts were visually checked for quality and consistency and remade if necessary.

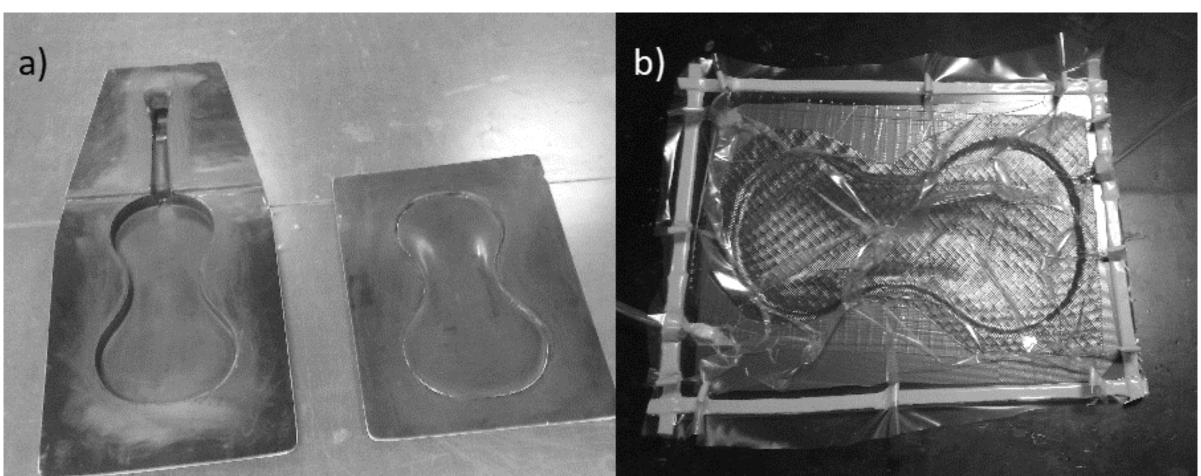


Figure 1 a) Glass fiber moulds for VARTM production of the body and soundboards of the violin. b) Production of a carbon fiber soundboard (UDC) through vacuum assisted resin transfer method (VARTM).

The lay-up for the composite soundboards was the following:

TwillC: 1 layer Twill-woven AKSACA™ A-38 200 tex (3k), 4 layers of unidirectional Tenax®-E HTS40/12K/HS, 1 layer Twill-woven AKSACA™ A-38 200 tex (3k).

UDC: 7 unidirectional layers of Tenax®-E HTS40/12K/HS.

Sandwich: 1 layer Twill-woven AKSACA™ A-38 200 tex (3k), Aramid honeycomb (thickness 1.5mm, density 29 kg/m³, cell size 3.2mm), 1 layer Twill-woven AKSACA™ A-38 200 tex (3k).

UDFlax: 5 layers of FLAXTAPE™ 200. FLAXTAPE™ 200 was dried in a drying oven for 1 hour on 105° Celsius prior to the VARTM process, as suggested by the manufacturer.

Figure 2: Thickness pattern of the soundboard for TwillC (TwillCA and TwillCB) from left to right: 1 layer Twill-woven AKSACA™ A-38 200 tex (3k), 4 layers of unidirectional Tenax®-E HTS40/12K/HS, 1 layer Twill-woven AKSACA™ A-38 200 tex (3k).

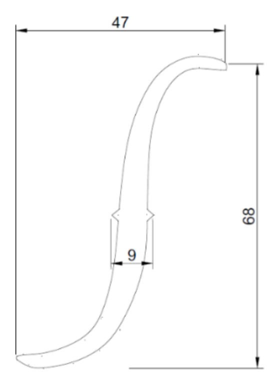


Figure 3: Design and dimensions of the soundhole for the prototype violins.

The design of the sound hole is slightly different than a conventional violin, but its dimensions fall within standard measurements (Fig. 3). The sound holes were 47mm wide and 68mm long. Both sound holes were 42mm apart. Nodges were carved up to 9mm, the widest point without the nodges was 6.3-6.4mm. The soundboards were fitted with a conventional spruce (P. Abies) bass bar (Fig. 4). All bass bars were made from the same piece of wood to limit variations in material properties like density, Young's modulus, and shear modulus. All the spruce soundposts of the instruments were made from a single piece of wood for similar reasons. The shape and size of the bass bar was conventional with a length of 26.7mm, thickness of 5.5mm at its base and height from 13mm at the center on the bridge position towards 3mm at the end. String length from the upper nut to the bridge is a standard 328mm, height of the bridge from the soundboard to the highest point of the bridge was 32-33mm. The strings on all violins were: *Dominant* g (133 medium synthetic core, silver wound), d (132a medium synthetic core, silver wound), a (131 medium synthetic core, aluminum wound) produced by Thomastik-Infeld GmbH © and *Kaplan* e (k420B-3 medium tinned carbon steel core) produced by D'Addario & Company, Inc. ©.

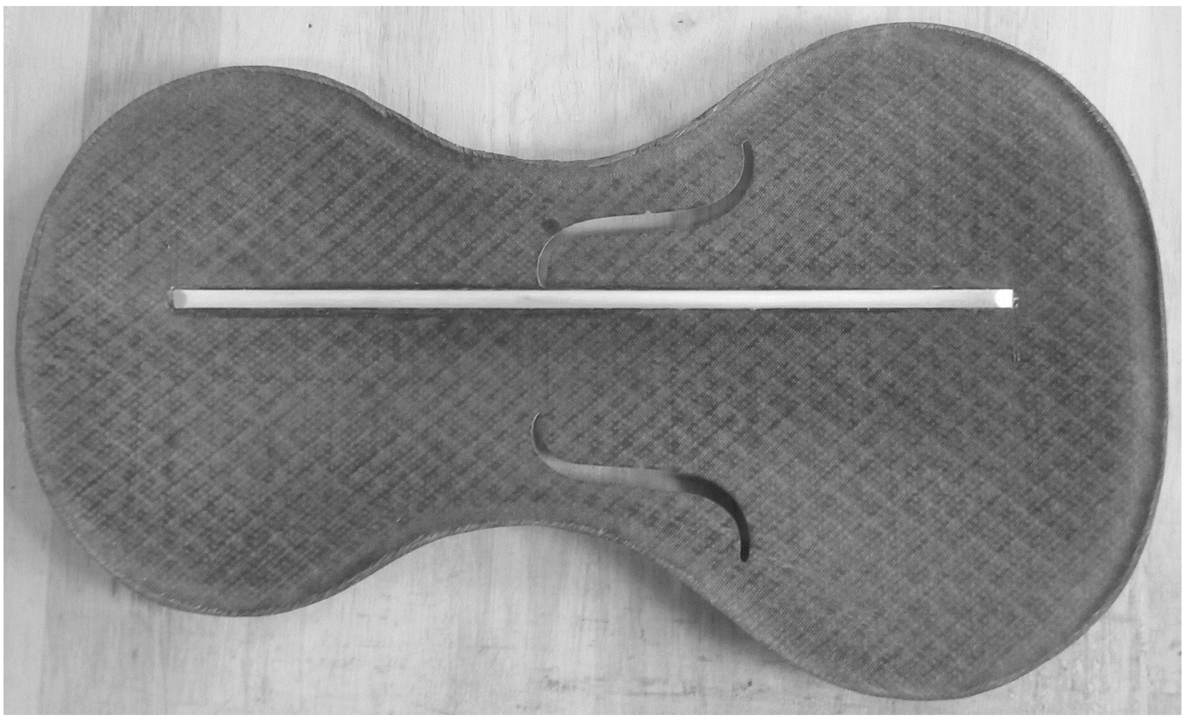


Figure 4: Produced soundboard (TwillCB) with sound holes cut and spruce bass bar fitted.

Table III: Total weight of the finished violin prototypes.

	Total weight of the violins (including strings and chinrest) (g)
Spruce	418
UDC	411
Sandwich	396
UDFlax	452
TwillCB	417
TwillCA	415

Damping measurements are derived from the modal analysis of beams cut along (longitudinal, l) and across the fibers (transversal, t) through impact excitation in the center of the beam and response measurement with 3 Polytec PSV 500 laser Doppler vibrometer directed at the left, middle and right side of the beam respectively (Table IV). Only the quality factor of the first mode of each beam is provided, which serves as an approximation of the damping properties of the material. The quality factor Q describes how much energy is lost during the resonating movement. A vibration with a high quality factor loses less energy over time and therefore has a lower damping.

Table IV Measured quality factors of beams cut along (l) and across (t) the fibers, from four spruce plates and six composite material plates produced by VARTM

Material		Quality factor
Spruce 1	l	120
	t	56
Spruce 2	l	154
	t	56
Spruce 3	l	170
	t	59
Spruce 4	l	86
	t	52
Flax UD 1	l	83
	t	32

Flax UD 2	l	98
	t	44
Carbon UD 1	l	946
	t	87
Carbon UD 2	l	570
	t	102
Carbon UD/ Woven	l	641
	t	491
Honeycomb/ Carbon woven	l	179
	t	189

<u>Additional information on the sound radiation measurements.</u>

Sound radiation measurements were performed in an anechoic chamber to reduce noise and the influence of room acoustics. The violin was mounted on a rig and excited with a miniature impact hammer (PCB 086E80), acoustic response was measured with a microphone (DPA 2006-C) at a distance of 33 cm from the bridge. The instrument was measured in 12 positions, with a 30° clockwise turn of the horizontal plane between each position. The measurement for each position consisted of 3 excitations, of which a complex average was calculated. The coherence function was used as a quality parameter, if the coherence was not consistently close to 1 the measurement was repeated. The entire measurement was performed with both horizontal (on the side of the bridge) and vertical excitation (on the top of the bridge). The Oberlin Acoustics App (ObieApp1.0b71) was used as acquisition software, which runs on a LabView platform.

Figure 5: set-up of the sound radiation measurement for horizontal excitation.

<u>Additional information on the listening tests.</u>

In the evaluation experiment, the violin player chose to play a modified piece of Symphony Espagnole by Édouard Lalo. In specific she chose part 4, pg 1, and modified it so that each string was played for approximately the same time. The excerpt played was approximately 88 seconds at its longest. All excerpts played were recorded with two Zoom H4N – Neuman microphones (km184NI). One microphone was placed approximately 1m behind the screen, the other approximately 4m further in the room. The recordings are_available for other researchers on request, please contact the main author. In the selection experiment, the two violin players first played a 3 octave scale starting from G_3 on each violin (34 seconds), followed by an excerpt of their choice from the 9th symphony by Antonin Dvořák (due to practical limitations this experiment could not be recorded).

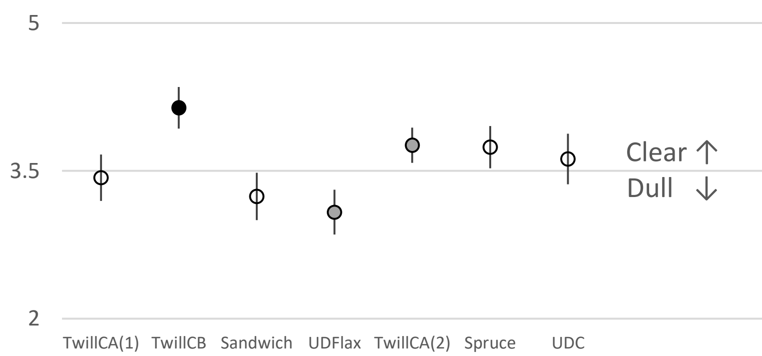
Additional results of the evaluation experiment:

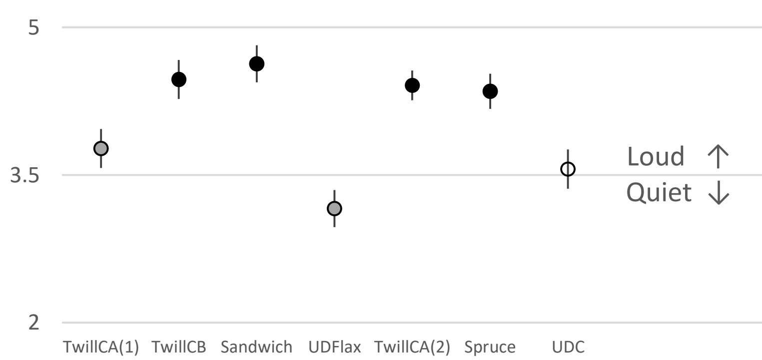
In addition to the fixed questions, listeners were also given the option to add **other words or remarks on the sound of each violin**. They left a total of 49 other remarks, the option was left blank 210 times. 30 of these remarks described the balance being good or bad and/or described particular strings or registers. No other trends were observed in the other 19 remarks.

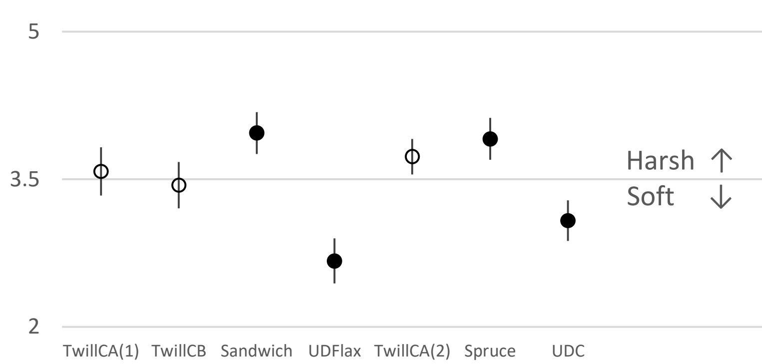
Listeners could indicate which instrument they would like to take-home, no large differences with the question what instrument is best were observed: UDFlax (9), TwillCB (7), TwillCA2 (6), Spruce (5), UDC (3), Sandwich (3) and TwillCA1 (2).

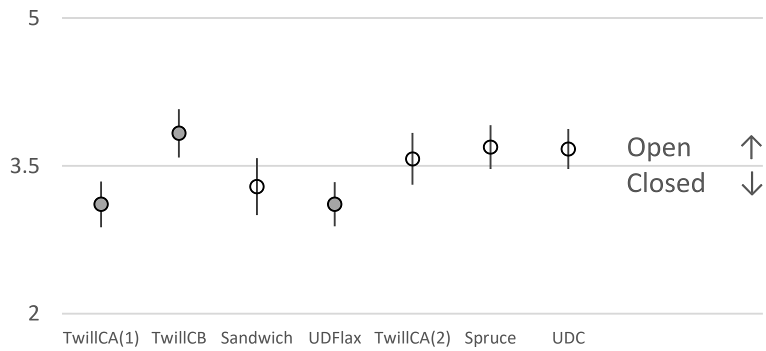
Figures showing the rating of the violins in evaluation task (mean +/-1 standard error of the mean).

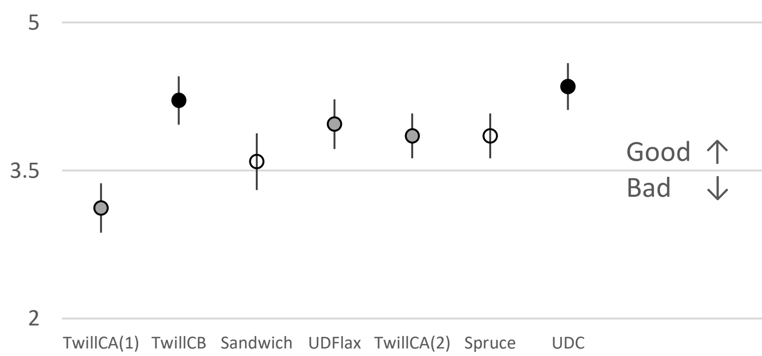
Filled brown dots indicate a statistically strong deviation (p-value<0.05) from the expected mean (3.5). Filled yellow dots indicate a weak deviation (p-value<0.1).

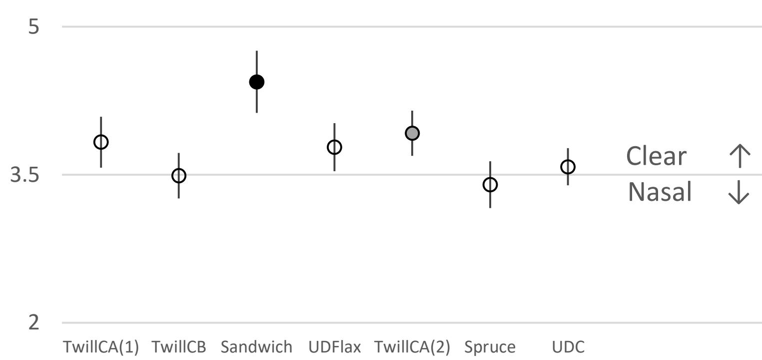

5
3.5
2
TwillCA(1)
TwillCB
Sandwich
UDFlax
TwillCA(2)
Spruce
UDC
Clear
Dull

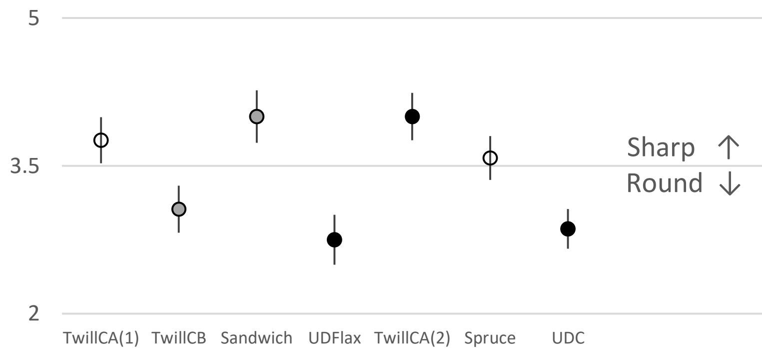

5
3.5
2
TwillCA(1)
TwillCB
Sandwich
UDFlax
TwillCA(2)
Spruce
UDC
Loud
Quiet

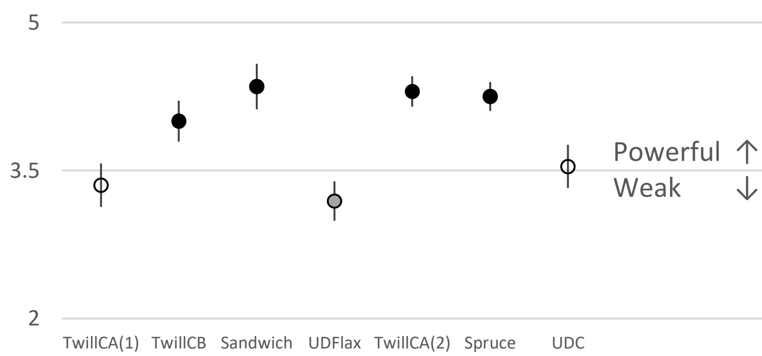

5
3.5
2
TwillCA(1)
TwillCB
Sandwich
UDFlax
TwillCA(2)
Spruce
UDC
Harsh
Soft


5
3.5
2
Open
Closed
TwillCA(1) TwillCB Sandwich UDFlax TwillCA(2) Spruce UDC


5
3.5
2
Good
Bad
TwillCA(1) TwillCB Sandwich UDFlax TwillCA(2) Spruce UDC


5
3.5
2
Clear
Nasal
TwillCA(1) TwillCB Sandwich UDFlax TwillCA(2) Spruce UDC





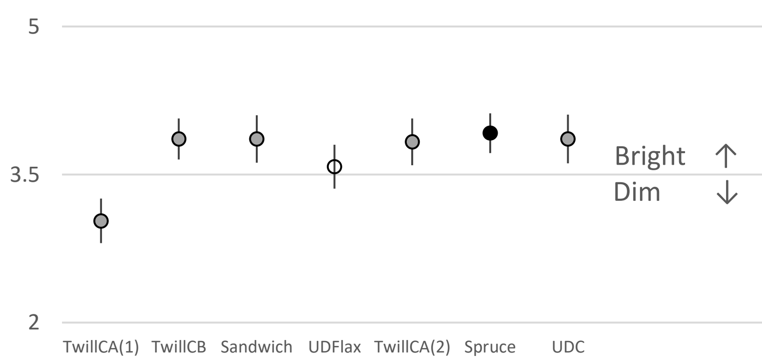


Figure 6: Mean score +/- SEM of the violins on the pairs of adjectives presented on a 8-point Likert scale. Filled black dots indicate a statistically strong deviation (p-value<0.05) from the expected mean (3.5 dotted line). Filled grey dots indicate a statistically weak deviation (p-value<0.1).

Order of presentation selection task. The order in which the different pairs were presented and their subsequent order was for Player 1: Conventional violin – TwillCB; Sandwich – Conventional violin; TwillCB – UDFlax; Conventional violin – UDFlax; TwillCB – Sandwich; UDFlax – Sandwich. Violin player 2: Sandwich – TwillCB; Conventional violin – Sandwich; UDFlax – TwillCB; Sandwich – UDFlax; TwillCB – Conventional violin; UDFlax – Conventional violin.

Additional results of the selection experiment.

In the selection experiment, listeners were asked to indicate why they chose a particular violin. As some violins were chosen more often than others, these are displayed in percentage to the amount of times a violin was chosen in figure 7.

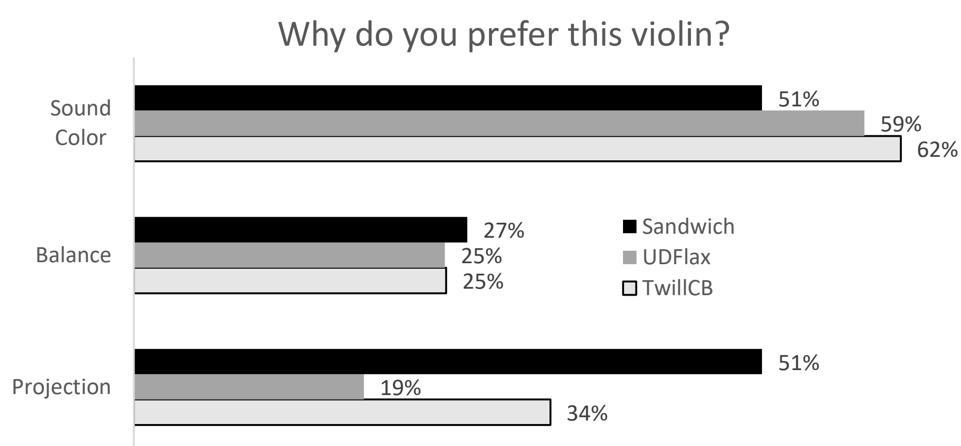


Figure 7: Reason why listeners chose a particular violin in the selection test.

Questionnaire evaluation task:

Dear participant,

During this experiment, you will hear 7 violins a number of times, each time for about 1 minute. The violins will always be presented in the same order. You will listen multiple times to respectively violin 1, 2, 3, 4, 5, 6, and 7.

On the following pages you will find an evaluation sheet for each violin, on which you will give your opinion on how the instrument sounds for you. Pay attention! The pages are printed <u>recto-verso</u>. On the last page you will find some general questions about the instruments and your personal background. <u>Please take care to fill in everything, otherwise your contribution can not be used for the research.</u>

You will be presented multiple scales with each time two words at the end of the scale. These two words function as the extremities of the scale. Each time you will indicate which word describes the sound best for you and in what amount. If you don't know the answer or don't have a preference between the two words you select the box 'I don't know'.

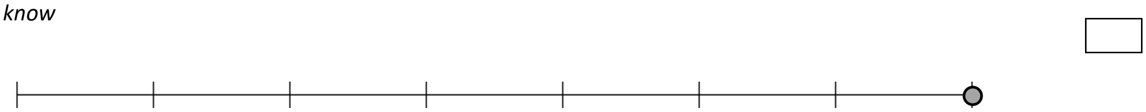
<u>If you don't understand something or have questions about how to fill out this questionnaire, please ask before the start of the experiment.</u> After the experiment the instruments will be revealed, then there is time and space for questions and discussion. This questionnaire is personal, please fill it out on yourself. If you don't know or if you don't have an opinion you can always select or write this.

You will give your answer on the scales with a dot on one of the vertical lines. With this questionnaire you will also receive a separate sheet on which more information about the different words is given.

Here are some examples on how to fill in the scale using the example of tasting different apple pies.

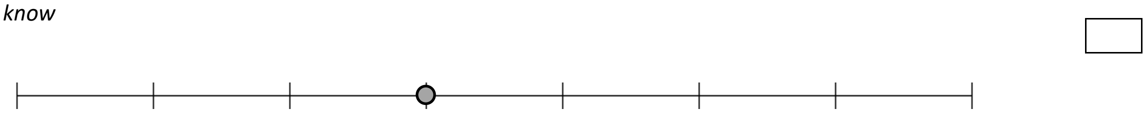
I think apple pie 1 tastes very sweet, so I put a dot at the extremity of the direction sweet.

Sour *Sweet* *I don't know*



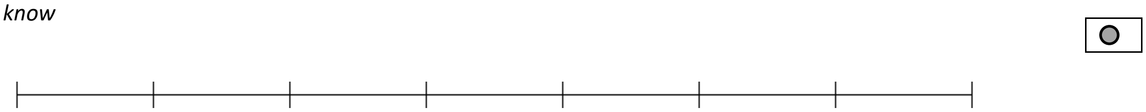
I think apple pie 2 is a bit more sour then sweet, but I don't think the sour taste is very pronounced or big. I put the dot on the scale to indicate this.

Sour *Sweet* *I don't know*



I don't know if apple pie 3 is more sour or sweet. I put a dot in the box 'I don't know'.

Sour *Sweet* *I don't know*



If you wish, you can indicate a preliminary opinion with a line above the scale, before later putting a dot somewhere on the scale.

Violin 1

Open Closed I don’t know

Round Sharp I don’t know

Quiet Loud I don’t know

Cold Warm I don’t know

Harsh Soft I don’t know

Powerful Weak I don’t know

Bad Good I don’t know

Rich Poor I don't know

Dull Clear I don't know

Bright Dim I don't know

Nasal Clear I don't know

Do you have other words or remarks on the sound of this instrument?

………

………

General questions

The best instrument is in my opinion Nr: ……………………………………………………………………………………………

The second best instrument is in my opinion Nr: …………………………………………………………………………..

The worst instrument is in my opinion Nr: ……………………………………………………………………………………

Which instrument(s) do you think have a wooden soundboard? Nr(s):……………………………………………….

Which instrument did you find most warm sounding?..

Which instrument did you find most powerful sounding?..

Which instrument did you think most rich sounding?..

What pair of words do you think is most important to judge the quality of a violin?

……….

How does a violin have to sound for you to be selected as best?

……

………

If I could take an instrument home I would take Nr: …………………………………………………………………….

Put a circle around what fits best:

I am a: student instrumentenbuilding student classical music teacher researcher other

Do you regularly play an instrument?

……….

If yes, what/which instrument(s) do you play?

……......

If yes, for how many years have you played an instrument?

……..

EXPLANATION WORDS SHEET

English:	**Dutch:**
open	**open**
Description: free, loose	Beschrijving: vrij, los
Contradiction: **closed**	Tegenstelling: **gesloten**
loud	**luid**
Description: a great volume in sound.	Beschrijving: een groot volume in klank.
Comparison: shouting is loud, whispering is silent.	Vergelijking: Roepen is luid, fluisteren is stil.
Contradiction: **quiet**	Tegenstelling: **stil**
warm	**warm**
Description: with depth.	Beschrijving: met veel diepte.
Comparison: some radio-presenters, often on late-evening broadcasts, have a very ‘warm’ voice.	Vergelijking: sommige radio-presentatoren, vooral op Klara en in laatavond programma’s, hebben een zeer ‘warme’ stem.
Contradiction: **cold**	Tegenstelling: **koud**
clear	**helder**
Description: without noise, lucid, light, pure.	Beschrijving: duidelijk en zonder bijgeluiden, klaar, licht, zuiver.
Contradiction: **dull**	Tegenstelling: **dof**
powerful	**krachtig**
Description: strong, overwhelming, muscled	Beschrijving: sterk, overweldigend, gespierd
Contradiction: **weak**	Tegenstelling: **zwak**
sharp	**scherp**
Description: cutting, pointy, penetrating	Beschrijving: snijdend, puntig, doordringend
Contradiction: **round**	Tegenstelling: **rond**
nasal	**nasaal**
Description: nose sound	Beschrijving: neusklank
Comparison: someone who talks with a closed nose, or sound that are carried through the nose like ‘n’ and ‘ng’.	Vergelijking: iemand die met een afgesloten neus praat, of klanken die door de neus naar buiten worden gedragen zoals ‘n’ en ‘ng’
Tegenstelling: **clear**	Tegenstelling: **helder**
harsh	**hard**
Description: something that is strongly expressed or pronounced. Solid and firm.	Beschrijving: iets dat sterk uitgedrukt of uitgesproken is. Vast en stevig.
Contradiction: **soft**	Tegenstelling: **zacht**
rich	**rijk**
Description: with many harmonic overtones, with a broad and full harmonic spectrum.	Beschrijving: veel harmonische boventonen, met een breed en vol spectrum
Contradiction: **poor**	Tegenstelling: **arm**
bright	**briljant**
Description: with a brilliance, sparkling, virtuoso	Beschrijving: Met een schittering, fonkelend, virtuoos

Contradiction: **dim** Tegenstelling: **glansloos**

Questionnaire selection task

Dear participant,

Thank you for participating in this blind listening test.

For each violin player, you will hear six pairs of violins. Please put a circle around the instrument that enjoys your preference and indicate why you chose this violin as favorite. You can select multiple reasons. If you choose Sound color, please describe it by putting a circle around the words that best describe said sound color for you. If you have other words to describe the sound, you can write these on the dotted line.

We will do this experiment with two violin players. The order in which the instruments are presented will be changed between the violin players.

If you have any questions regarding this questionnaire please ask them before the start of the experiment. After the test is concluded the instruments will be revealed and there will be time for additional questions.

What instrument(s) do you play: …………………………………………………………………….

How many years do you play a musical instrument: ………………………………………………….

Violinist nr. 1

Pair 1: Violin nr. 1 Violin nr. 2

○ Better projection

○ Better balance

○ Better sound color

warm harsh clear rich open sharp round bright powerful nasal ……………………………

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Tables

Table I: Weight of the finished soundboards, engineering constants calculated using eLamX² and estimation of damping of the materials. The damping is an approximation in comparison to spruce, which was given the 0 value as the benchmark material.

Soundboard	Weight (g)	D11 (Nmm)	D22 (Nmm)	D66 (Nmm)	Damping
Spruce	74.8	15.8	1.1	1.5	0
UDFlax	100.3	14.7	0.9	1.2	0/+
UDC	72	14.7	0.9	0.6	--
TwillCA	71	15.5	6.4	0.7	--
TwillCB	74.8	15.5	6.4	0.7	--
Sandwich	42.3	15.7	15.7	0.7	-

Table II: Strong and weak evidence to reject the null-hypothesis and link adjectives to the sound of each of the seven investigated violins.

	Strong evidence (p-value<0.05)	Weak evidence (p-value<0.1)
TwillCA(1)	dim	loud, closed, bad
TwillCB	warm, clear, loud, good, powerful, rich	open, round, bright
Sandwich	loud, harsh, nasal, powerful	sharp, rich, bright
UDFlax	warm, soft, round	dull, quiet, closed, good, weak, rich
TwillCA(2)	loud, sharp, powerful	warm, clear, good, nasal, bright
Spruce	loud, powerful, rich, bright	harsh, good
UDC	warm, soft, good, round	bright

Table III: Preference of listeners for composite violins when presented in pairs during our selection experiment. The pairs with the conventional violin are excluded as these were not a double-blind condition.

Number of participants favoring a specific violin and the reason why				
Player 1	**Preference listeners**	**Projection**	**Balance**	**Sound Color**
TwillCB	25	13	5	12
UDFlax	13	2	5	9
TwillCB	34	13	13	21
Sandwich	6	5	2	3

UDFlax	24	3	8	17
Sandwich	14	11	4	5
Player 2				
TwillCB	29	12	6	18
UDFlax	8	3	0	5
TwillCB	18	0	3	13
Sandwich	20	9	5	9
UDFlax	22	3	2	12
Sandwich	16	9	2	9

Figure captions

Figure 1: Prototype violins with soundboards from 5 different materials constructed for the study. Only one of the TwillC violins is displayed here as the two instruments are visually identical.

Figure 2: Mean value (dot) +/- 1 Standard error of the mean SEM (vertical line) of the violins' rating on the attributes warm – cold and rich – poor. Filled black dots indicate a statistically strong deviation (p-value<0.05) from the expected mean (3.5 dotted line). Filled grey dots indicate a statistically weak deviation (p-value<0.1).

Figure 3: Amount of times each violin was chosen as best, second best and worst in the evaluation experiment.

Figure 4: Amount of times each instrument was chosen on the question 'Which instrument did you find most rich/most powerful/most warm'.

Figure 5: Amount of times a pair of words was written down as important to judge the quality of a violin. In black the pairs prompted by a previous question, in gray the non-prompted pairs. Between the prompted pairs warm – cold and rich – poor, attributes related to the sound color, were chosen significantly more than powerful – weak, an attribute often linked to projection and loudness.

Figure 6: a) RMS level of the recording made during the evaluation experiment. b) acoustic sound radiation of all violins measured in an anechoic chamber with impact hammer excitation. Frequency response functions (FRF's) smoothed over one tone for readability and interpretation purposes.

Figure 7: Percentage distribution on the description of the favored sound color for each of the violins.