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Listener evaluations of violins made from composites

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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, Lessard, and Babu, Acoust. Aust. **43**, 117–122 (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 an investigation of 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. *© 2020 Acoustical Society of America.*

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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*). It is said that, due to environmental changes and other factors, wood for music instruments is not only becoming more scarce and expensive, but it is also reducing 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 has been found in the literature. Most studies are limited in this regard because the violins tested were constructed independently from the research and can therefore vary in a number of attributes unknown to the researcher, such as 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 and, as a consequence, all other parameters are 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 and 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 violins.

II. CONSTRUCTION OF THE PROTOTYPE VIOLINS

The goal was to build all violins identically 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 CFRP produced by vacuum assisted resin transfer method (VARTM) was

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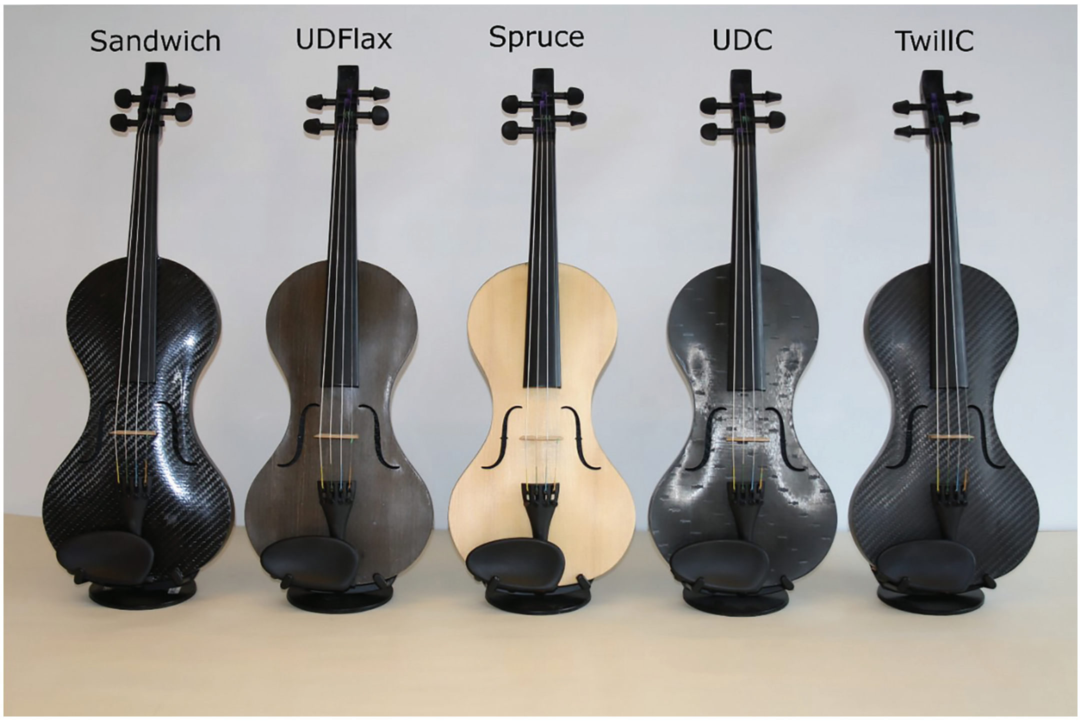

FIG. 1. (Color online) Prototype violins with soundboards from 5 different materials constructed for the study. Only one of the TwillC violins is displayed here as the two instruments are visually identical.

chosen as a quick and reliable way to produce the back, sides, and neck in one piece in a consistent way (video can be found in Ref. 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 of 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 classical laminate theory. The required thickness for each of these materials was calculated using the ELAMX[2] software package.[18] The composite soundboards were produced by VARTM. More detailed information on the materials, model, and production method are provided in supplementary material[15] and Ref. 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 (supplementary

TABLE I. Weight of the finished soundboards, engineering constants calculated using ELAMX (Ref. 2) 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	—

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material[15]). 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. As a result, 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 an eight-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] Second, 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" (supplementary material[15]). 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 min, 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 s 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 1 m 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 s) 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 Sec. V.

Figure 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 (supplementary material[15]).

Figure 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 in supplementary material[15]). 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

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

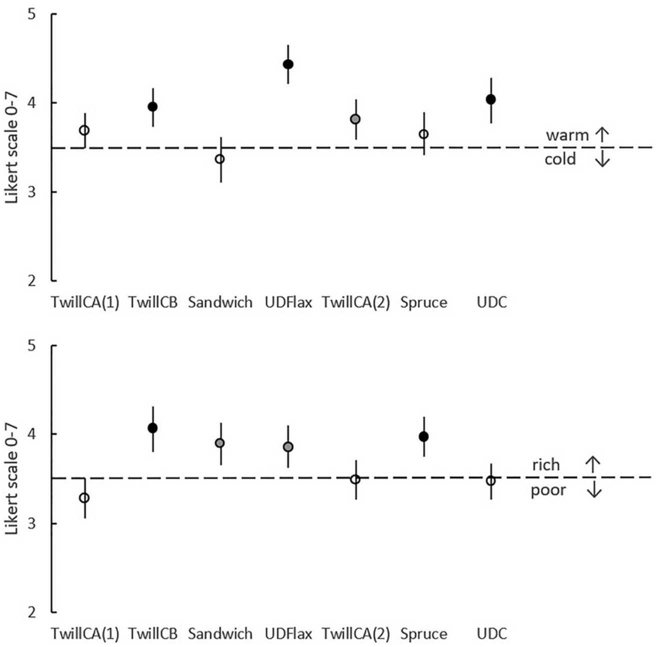

FIG. 2. Mean value (dot) +/−1 Standard error of the mean SEM (vertical line) of the violins' rating on the attributes warm–cold and rich–poor. Filled black dots indicate a statistically strong deviation (p-value <0.05) from the expected mean (3.5 dotted line). Filled grey dots indicate a statistically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

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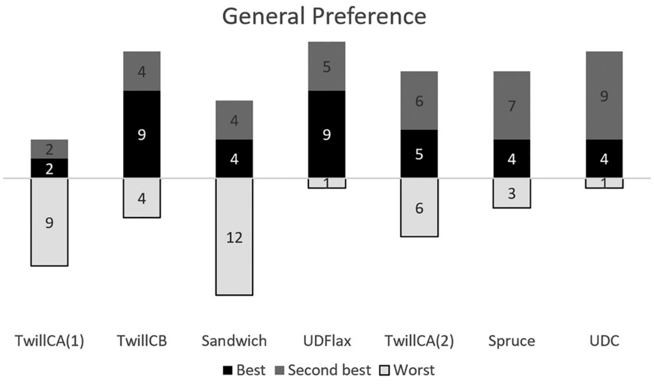

FIG. 3. Amount of times each violin was chosen as best, second best and worst in the evaluation experiment.

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 Fig. 5.

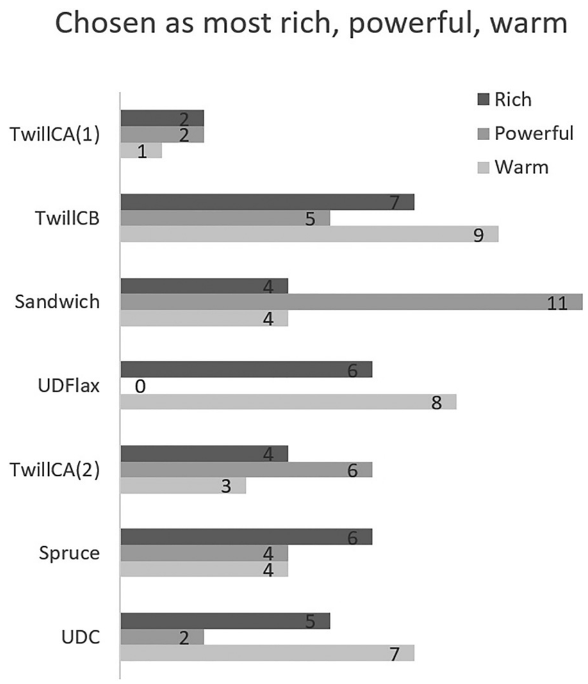

FIG. 4. Amount of times each instrument was chosen on the question "Which instrument did you find most rich/most powerful/most warm."

FIG. 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.

When we examine the root-mean-square (RMS) level of the audio recording made during the evaluation experiment [Fig. 6(a)] 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 an anechoic chamber [Fig. 6(b), more info in supplementary material[15]]. 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

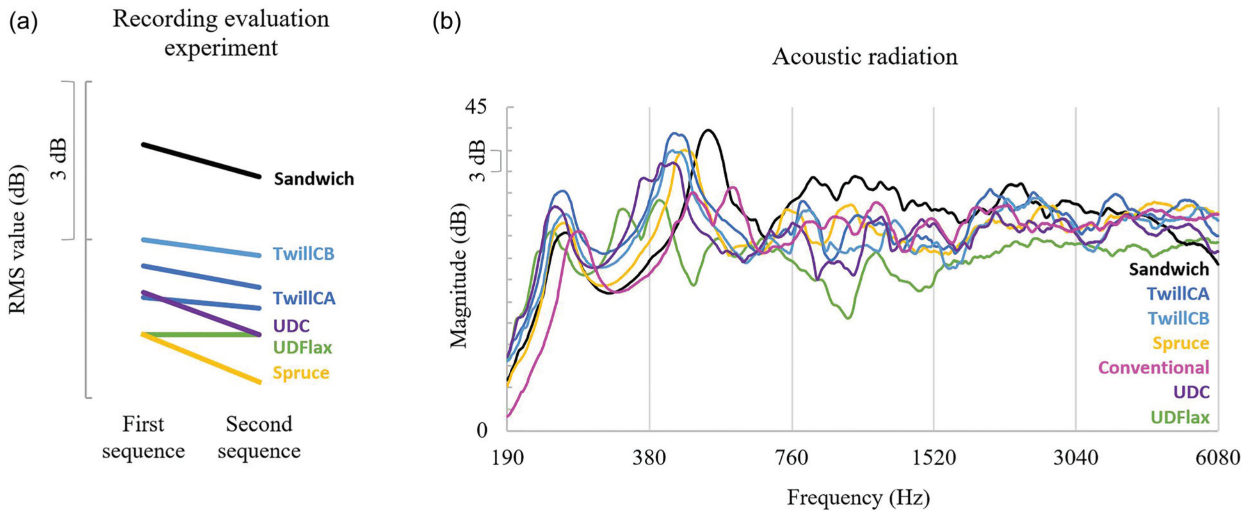

FIG. 6. (a) RMS level of the recording made during the evaluation experiment. (b) Acoustic sound radiation of all violins measured in an anechoic chamber with impact hammer excitation. Frequency response functions (FRF's) smoothed over one tone for readability and interpretation purposes.

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 the "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. 6(b)] 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 Ref. 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 s) on each violin, followed by a short piece of music of their own choice (20–30 s) on each violin (supplementary material[15]). 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

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

tests so the order of presentation was balanced (supplementary material[15]). 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. Second, 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 in supplementary material.[15])

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 supplementary material[15]). 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.

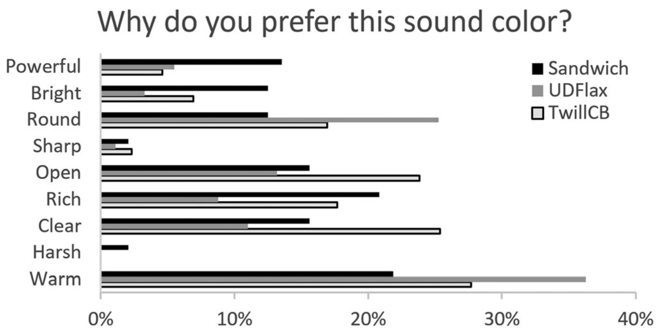

FIG. 7. Percentage distribution on the description of the favored sound color for each of the violins.

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 causes 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 the creation of 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. 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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