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1 Listener evaluations of violins made from 2 composites. 3

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19 **ABSTRACT**

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

33 I. INTRODUCTION

34 The soundboard of a violin has, with few exceptions, always been made out of wood, more
35 specifically of high quality spruce (*Picea Abies*). However, due to environmental changes and
36 other factors, wood for music instruments is said to be depleting, becomes more expensive, but
37 also lowers in quality¹. Meanwhile, the increase in use of technical composites such as carbon
38 fiber reinforced polymer (CFRP) and their qualities with regard to moisture stability and
39 durability, has generated research that investigates their material properties and compares them to
40 wood²⁻⁴. Consequently, in recent years, research has resulted in prototypes and commercially
41 available instruments made from composites⁵⁻⁹. However, no comparative studies that assess the
42 sound of composite violins with the same design and setup under controlled conditions is found
43 in literature. Most studies are limited in this regard because the violins to be tested were
44 constructed independently from the research and can therefore vary in a number of attributes
45 unknown to the researcher, like the model, quality of the materials used, construction method or
46 setup¹⁰⁻¹⁴. In the present study, the influence of the soundboard material is our focus, as a
47 consequence, all other parameters are taken as similar as possible among the tested violins. Under
48 these conditions, we consider the following questions: How do these composite violins sound?
49 Which variations in the construction of the soundboard influence the volume and timbre of the
50 sound? What possible quality factors are more important to the listeners? What possibilities do
51 composite materials offer to expand on the violin's sonic palette as we know it today?

52 To answer these questions six composite violins were designed and built with top plates from
53 different materials. We ran two experiments with the instruments; the first consisted of an
54 evaluation task with 37 participants, the second of a selection task with 40 participants. In both
55 cases, we examined how experienced listeners judged the timbre of the instruments on a broad

56 spectrum of possible qualities. We examined which instruments were favored, and why, in order
57 to shed light on what sound listeners prefer from such composite violin.

58 **II. CONSTRUCTION OF THE PROTOTYPE VIOLINS**

59 The goal was to build all violins identical except for the top plate, which was made from different
60 materials between the violins. To achieve this goal, all prototype violins were constructed by the
61 same luthier. A carbon fiber reinforced polymer (CFRP) produced by vacuum assisted resin
62 transfer method (VARTM) was chosen as a quick and reliable way to produce the back, sides and
63 neck in one piece in a consistent way (Video¹⁵ showing the production process on a cello). The
64 soundboards were made either from a selection of four composite materials or from spruce,
65 which was added as a reference material (Fig. 1):

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

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

76 As the used composite materials have a higher longitudinal Young's modulus than wood, the
77 thickness of the laminate can be decreased in order to have a similar bending stiffness as a spruce

78 plate. The bending stiffness of a plate is thought to be crucial to the sound of a wooden
79 instrument¹⁶, therefore it is taken as a guide to make these novel composite violins. Soundboards
80 of old conventional violins deform most often along the axis of the instrument¹⁷. Contemporary
81 luthiers therefore aim to make an arching stiff enough to be durable, without making it too stiff,
82 which is thought to be disadvantageous to the sound production of the violin¹⁶. As composite
83 materials offer a variety in anisotropy, the bending stiffness along the axis of the instrument
84 (D11) was chosen as the primary design criteria. The bending stiffness (or plate rigidities) are
85 derived from the ABD-Matrix of the Classical Laminate Theory. The required thickness for each
86 of these materials was calculated using the eLamX² software package¹⁸. The composite
87 soundboards were produced by VARTM. More detailed information on the materials, model, and
88 production method are provided in Appendix and¹⁹. Weight of the soundboards, calculated
89 bending stiffness's D11 (along the axis/longitudinal), D22 (transversal/radial), D66 (shear) and
90 damping of the materials are provided in Table I. The plate rigidities show the variety in
91 anisotropy between the materials. The damping is an approximation derived from the measured Q
92 factor of the first frequency of flat beams which were made in our lab by VARTM (Appx). As
93 this damping value is dependent on the mode measured, the exact value could be misleading.
94 Therefore the damping is given as an approximation in relation to spruce (0), our benchmark
95 material.

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

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

105 **III. THE EVALUATION EXPERIMENT**

106 **A. Methodology**

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

118 In the first listening test the members of the audience, rated the six violins individually on a
119 number of attributes. This method was chosen as it is a common way to judge instruments or
120 musicians in competitions, giving the test a high verisimilitude. For each violin, the attributes
121 were presented on a 8-point Likert scale between two opposite adjectives. Most invited
122 participants had Dutch as their mother tongue. As no study that uses Dutch words to describe the

123 sound of violins was available in the literature, a common language had to be defined with the
124 participants. First a list of English words was compiled from scientific literature^{11, 20}. Secondly,
125 multiple listeners who would take part in the experiment were asked which words they would like
126 to use for judging violins in Dutch and English as well as how they would translate these words
127 between the two languages. Also the participants were asked how they would like to be
128 questioned. Through this method an expert audience negotiated and agreed on the meaning of
129 pairs of adjectives that could be understood as each other's opposite, with the Dutch translation in
130 brackets: warm (warm) – cold (koud), clear (helder) – dull (dof), loud (luid) – quiet (stil), soft
131 (zacht) – harsh (hard), open (open) – closed (gesloten), good (goed) – bad (slecht), nasal (nasaal)
132 – clear (helder), round (rond) – sharp (scherp), powerful (krachtig) – weak (zwak), rich (rijk) –
133 poor (arm), bright (briljant) – dim (glansloos). Although a unipolar scale is usually recommended
134 in this type of research²⁰, the participants preferred a bipolar scale.

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

144 First, as requested by the participants, four random instruments (decided by draw) were played
145 (Spruce, UDFlax, TwillCB and Sandwich) to allow the listeners time to get familiar with the

146 acoustics of the hall and the sound of the prototype instruments. The order in which the
147 instruments were presented for the actual experiment was decided by random draw and was:
148 TwillCA(1), TwillCB, Sandwich, UDFlax, TwillCA(2), Spruce, UDC. TwillCA was presented
149 two times unbeknownst to the audience. If TwillCA scores similar both times, this would be a
150 good indication that a difference between violins can be taken as a difference in the sound
151 produced and not a difference in playing or order effect or fatigue.

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

163 During the entire evaluation experiment, the violinist was positioned on stage approximately 1m
164 behind a lightweight polyester fabric screen. The violin player was blinded with a sleeping mask
165 and the scent of the instruments was covered with a perfume. The instruments were handed to the
166 musician in the predetermined order by a researcher. The lights on stage were dimmed during the
167 test, but left on in the seating area, in order to make sure that the audience could not distinguish
168 the different instruments behind the screen. The violinist played the instruments with her own

169 bow. As in previous studies the bow is regarded in this experiment as an extension of the player's
170 body¹²⁻¹⁴. She played a musical fragment of her own choice (88 seconds) to evaluate the violins,
171 as a musician would normally do when evaluating an instrument. The experiment was recorded
172 for further analysis. The violin player was not questioned during the test, to minimize the time in-
173 between the playing of the instruments. After the test the violin player was asked by the
174 researcher what her favorite instrument was, and if she had any other remarks.

175 **B. Results**

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

186 To investigate how reliable these results were, a paired t-test of TwillCA(1) and TwillCA(2) was
187 performed. This test revealed a statistically significant improvement (p-value<0.05) in the rating
188 of TwillCA(2) on four (out of 11) of the bipolar scales powerful – weak (+0.946), loud – quiet
189 (+0.686), bright – dim (+0.829) and good – bad (+0.781) in comparison to the rating of
190 TwillCA(1). This is likely due to the order effect and is discussed in section V.

191 Fig. 2 shows the rating for two bipolar adjectives: rich – poor and warm – cold. Rich has been
192 shown to be the most important quality for violinists in a previous study²¹, while warm is often
193 used to describe the sound of conventional wooden violins in comparison to other materials.
194 TwillCB, UDFlax and UDC show large statistic deviations from the expected mean a random
195 distribution would show towards *warm*. For *rich – poor* only TwillCB and Spruce show a
196 statistically strong deviation towards *rich*. The scale from 2 to 5 was chosen as all our calculated
197 means +/- standard error of the mean (SEM) fit within this scale (Appx).

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

201 Listeners were asked which instrument they found “most rich/most powerful/most warm” (Fig.
202 4). Interestingly TwillCA(2) was preferred more than TwillCA(1), this corresponds with a
203 consistently higher mean score on positive attributes like: *powerful* (+0.95), *bright* (+0.83), *good*
204 (+0.78) and *loud* (+0.69) (Figures Appx). The differences could be explained by the order.
205 TwillCA(1) was the first to be heard, TwillCA(2) came after UDFlax and before Spruce. As
206 UDFlax was never chosen on the question ‘Which instrument did you find most powerful?’,
207 TwillCA(2) may have appeared more powerful in contrast.

208 Listeners were asked which pair of adjectives they found were “most important to judge the
209 quality of a violin?” (Fig 5). Three of the bipolar pairs were prompted by the previous question
210 “Which instrument did you find most rich/most powerful/most warm”, and so listeners might
211 have a positive bias towards these pairs. *warm – cold* (13) and *rich – poor* (12) scored higher than
212 *powerful – weak* (2). This finding can be interpreted as follows: either these listeners find the
213 power of the sound of a violin secondary to the sound color, or they could have (either

214 intentionally or unintentionally) favored sound color over power in an effort to rate attributes
215 which are thought to be related to wood. The pairs *loud – silent*, *harsh – soft* and *good – bad*
216 were never written down and are therefore not included in Figure 5.

217 When we examine the Root-Mean-Square (RMS) level of the audio recording made during the
218 evaluation experiment (Fig. 6a) the Sandwich violin stands out with the highest RMS level. RMS
219 level is a measure of the average value of a waveform over time and is an approximation of the
220 acoustic sound level perceived by our ears. The violins with a top plate made from a material
221 with a higher degree of anisotropy: UDC, UDFlax and Spruce have a slightly lower RMS value
222 compared to the other violins. To rule out the effect of the player, additional acoustic radiation
223 measurements of the violins were performed with an impact hammer in an anechoic chamber (Fig.
224 6b, more info in appendix). These measurements show that the Sandwich violin is the most
225 effective sound radiator between approximately 400 and 4000 Hz. UDFlax is the least effective
226 sound radiator between the measured violins above 400 Hz. Below 400 Hz, the violins with a
227 soundboard made from unidirectional composites, UDC and UDFlax, have the highest average
228 acoustic response.

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

233 **IV. THE SELECTION EXPERIMENT**

234 **A. Methodology**

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

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

258 In this second experiment, the four violins were presented in pairs to 40 listeners, all members of
259 the Ghent University Orchestra (GUSO). The listeners had an average of 14 years of experience
260 playing music instruments. Fifteen listeners were violin players. The instruments were played
261 behind the same screen as during the first experiment. The selection experiment took place in a
262 200-seat hall Trechterzaal, Thermanal, Ghent University.

263 The format of the listening test was based on the one used in¹⁴. The test was conducted twice with
264 a different violin player for each part. The violin players were members of the orchestra. To
265 judge each pair of violins, the musicians first played a scale (34 seconds) on each violin, followed
266 by a short piece of music of their own choice (20-30 seconds) on each violin (Appx). This so-
267 called ABAB format of the experiment made it possible for listeners to hear each violin twice,
268 that is both before and after the other violin¹⁴. In this way, each musician presented all the violin
269 pairs in ABAB format (Table III). Between the two musicians, the order in which the pairs were
270 presented and which violin went first in a pair was changed over the two tests so the order of
271 presentation was balanced (Appx). In the questionnaire, the listeners were asked which
272 instrument they preferred and why. Listeners could skip a certain pair if they did not have a
273 preference. Secondly, they were given three quality factors: ‘better projection’, ‘better balance’
274 and ‘better sound color’. They were asked to choose any number of those quality factors that
275 explained why they chose the said violin. If they chose ‘better sound color’, they could further
276 specify their choice using a list of selected adjectives to describe that sound color in more detail.
277 They had the option to add additional remarks to explain their preference. (Questionnaire Appx).

278 **B. Results selection experiment**

279 As a summary of the results shows in Table III, TwillCB was preferred by most of the listeners
280 over UDFlax with both violin players. Listeners clearly favored TwillCB over Sandwich when

281 listening to player 1 but did not in the case of player 2. UDFlax was favored over Sandwich in
282 both cases.

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

293 **V. DISCUSSION**

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

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

301 As expected, our experiments show that by using a variety of composite materials for
302 soundboards of violins, a wide range of sounds and timbres can be produced. As the use of these

303 composite materials allow violin makers to change the sound of a violin in a number of ways,
304 they can offer new artistic opportunities for violin players and composers to explore. Therefore,
305 these findings could have implications for the future development and production of music
306 instruments as well as future musical compositions and performances.

307 The low ratio of stiffness/density of the flax composite material resulted in a higher weight for
308 the finished soundboard in comparison to the other materials. In the acoustic radiation
309 measurements, UDFlax was the least effective sound radiator between our violins. It is therefore
310 not surprising that the instrument was the least associated with attributes linked to loudness, such
311 as powerful and projection. Our results confirm the theory²² that a material with a lower ratio of
312 stiffness/density and higher damping is a less efficient sound radiator, resulting in a less powerful
313 or loud sound. Although this instrument was the least favored by our violin player in the
314 evaluation task, it was preferred by many listeners for its warm and round sound color.

315 The instrument made from a lightweight, low damping and low anisotropy sandwich material
316 consisting of carbon and an aramid honeycomb (Sandwich) was mostly chosen as most powerful,
317 had the highest mean for loud, had the highest RMS value and sound radiation measured and was
318 the only instrument being favored largely for its projection. Yet this instrument was the least
319 preferred in our evaluation task and least picked as favorite in our selection task when played by
320 the first violin player, but was more liked when played by the second player. These findings are
321 in line with a previous study¹⁴ showing that violins with the best projection are not always chosen
322 as favorite by listeners. Listeners' evaluations can be influenced by the performer's way of
323 playing the instrument. In our evaluation experiment, this violin's sound color was described as
324 harsh. This is less clear in our selection experiment, as the nature of this experiment emphasizes
325 the positive qualities of each instrument.

326 UDC, with a higher anisotropy than TwillCA and TwillCB, was described as round and soft and
327 was chosen less as powerful. This could be an indicator that for composite materials, a higher
328 degree of anisotropy results in an instrument with a round and soft tonal color preferred by many
329 listeners, but with a less powerful sound. This is in line with the simulations performed by Viala²³
330 that showed variations in anisotropy to have a significant effect on certain modes of the violin.
331 Indeed, the modes for which the radial direction is important will have a lower frequency and
332 more damping when the radial stiffness (E_r) is lower (which is the case when the anisotropy is
333 high), which intuitively goes well with a less powerful but rounder sound. More research is
334 definitely needed to investigate this aspect and correlate it with numerical predictions.

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

346 When we compare the results from TwillCA to TwillCB, the two instruments with identical top
347 plate materials, it is clear that the instruments were rated differently in our evaluation task. More
348 research is needed to understand what is the cause of these differences. When we examine the

349 scores of TwillCA(1) and TwillCA(2) we observe some differences in attributes that are linked to
350 loudness like powerful or loud. A possible explanation for this finding is that TwillCA(2) was
351 presented after UDFlax, the least powerful and loud instrument. As the listeners had just heard
352 UDFlax, they rated TwillCA(2) in relation to this, resulting in a different score in adjectives
353 related to projection. As TwillCA(1) was the first violin played, it could have been affected by
354 the order in which the instruments were presented. The order effect of the sequence on the rating
355 of violins is not well documented in literature. Research on judge bias in the Idol series shows
356 that in a sequence of seven, the score of the first contestant has the highest negative mean bias²⁴.
357 As such, it is feasible that TwillCA(1) was affected by a negative bias due to the order effect.

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

367 As the experiments presented investigate the sound of these violins from a listener perspective,
368 the perception of these violins by violin players is outside the scope of this study. As the
369 preference of the violin player in our first experiment was the exact opposite of the trend shown
370 by the listeners, it is evident this must be examined further in future experiments. Additionally,
371 examining how these instruments are perceived when they are accompanied by an orchestra or

372 played in an ensemble can provide valuable psychoacoustic insights. Finally, the vibro-acoustical
373 behavior of these violins could be further examined through modal analyses, which would give a
374 deeper understanding on the effect of the material properties on the body shell response of music
375 instruments.

376 **VI. CONCLUSION**

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

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

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

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

406 **Acknowledgements**

407 We thank all musicians and listeners who took part in these experiments for their dedication and
408 patience during the experiments. We thank FWO (Research Foundation Flanders grant nr.
409 1180217N) for funding this research. Ghent University and Hogent – School of Arts Ghent for
410 providing logistic support. We would like to thank Matthieu Libeert for consulting throughout
411 production of the composite parts using VARTM. Thanks also to Patrick Housen, who recorded
412 the evaluation experiment. Thanks to Lineo for donating FLAXTAPE™ that was used to make
413 the UDFlax violin.

Appendix

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

418 *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

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

426 *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

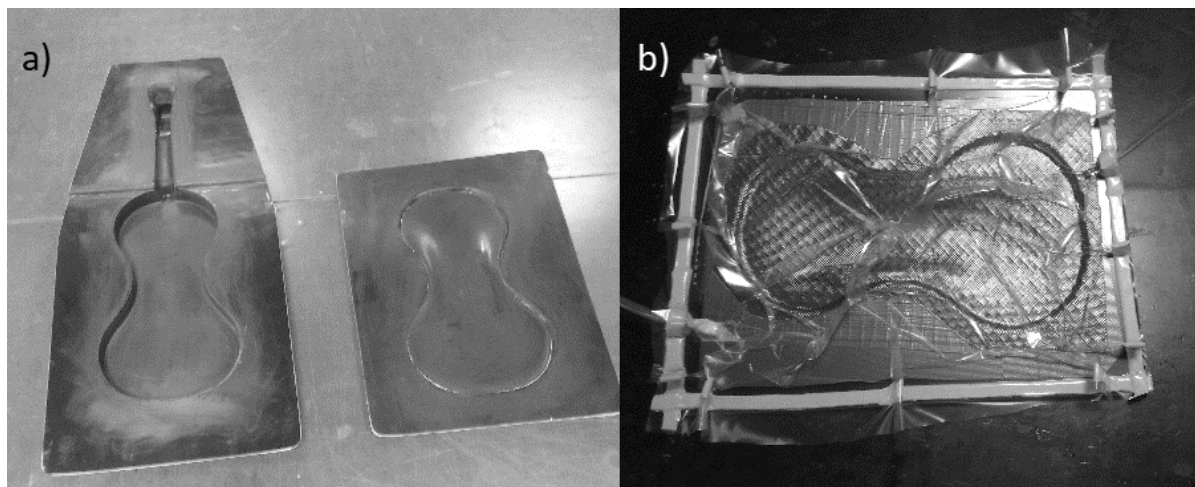
427 Sources:

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

430 Kersemans M., Martens A., Lammens N., Van Den Abeele K., Degrieck J., Zastavnik F., Pyl L., Sol H., Van
431 Paepegem W. (2014) Identification of the Elastic Properties of Isotropic and Orthotropic Thin-Plate
432 Materials with the Pulsed Ultrasonic Polar Scan. *Experimental Mechanics* 54:1121–1132.
433 Phillips S., Lessard L. (2011) Application of natural fiber composites to musical instrument top plates.
434 *Journal of Composite Materials* 46(2): 145–154.
435 CES Edupack 2019 19.2.0 (2019) Granta Design Limited, Cambridge, United Kingdom.

436
437 As the materials varied in Young’s modulus, but needed a similar longitudinal bending stiffness for
438 consistency, the required thickness for each material was calculated based on a thickness pattern usually
439 used in violinmaking. For the spruce top plate this was 3mm at its thickest in the center going towards
440 2.2mm at the outer edges. This calculation was done using the eLamX² software package that uses the
441 Classical Laminate Theory. Through this method the thickness pattern for spruce was converted into a
442 longitudinal stiffness pattern (D11) that could be used to calculate the required thickness of each
443 composite material. All soundboards were infused (VARTM) using the same epoxy resin as the bodies
444 (See figure 1). Parts were visually checked for quality and consistency and remade if necessary.

445



446
447 *Figure 1 a) Glass fiber moulds for VARTM production of the body and soundboards of the violin. b) Production of a carbon fiber*
448 *soundboard (UDC) through vacuum assisted resin transfer method (VARTM).*

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

450 TwillC: 1 layer Twill-woven AKSACA™ A-38 200 tex (3k), 4 layers of unidirectional Tenax®-E
 451 HTS40/12K/HS, 1 layer Twill-woven AKSACA™ A-38 200 tex (3k).
 452 UDC: 7 unidirectional layers of Tenax®-E HTS40/12K/HS.
 453 Sandwich: 1 layer Twill-woven AKSACA™ A-38 200 tex (3k), Aramid honeycomb (thickness 1.5mm,
 454 density 29 kg/m³, cell size 3.2mm), 1 layer Twill-woven AKSACA™ A-38 200 tex (3k).
 455 UDFlax: 5 layers of FLAXTAPE™ 200. FLAXTAPE™ 200 was dried in a drying oven for 1 hour on 105°
 456 Celsius prior to the VARTM process, as suggested by the manufacturer.

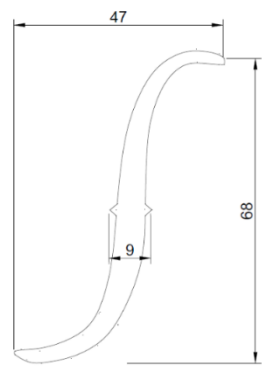
457
 458



459
 460
 461
 462

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).

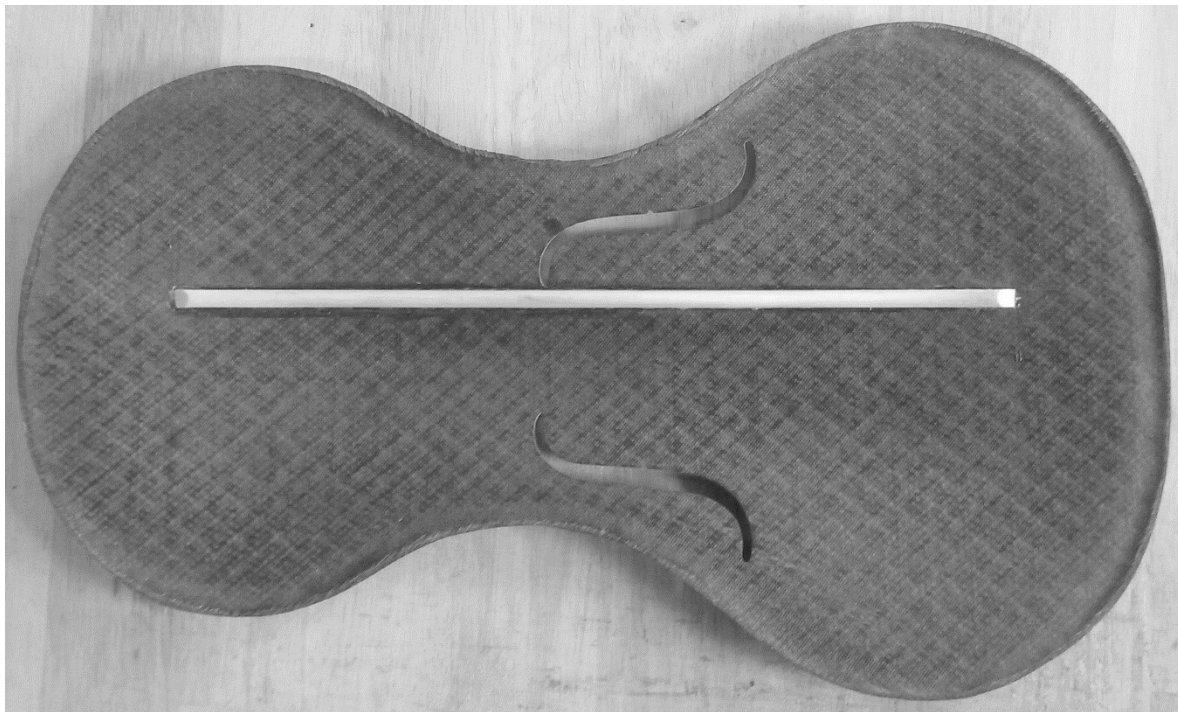
463 The design of the sound hole is slightly different than a conventional
 464 violin, but its dimensions fall within standard measurements (Fig. 3).
 465 sound holes were 47mm wide and 68mm long. Both sound holes were
 466 42mm apart. Nodges were carved up to 9mm, the widest point without
 467 nodges was 6.3-6.4mm. The soundboards were fitted with a
 468 conventional spruce (P. Abies) bass bar (Fig. 4). All bass bars were
 469 from the same piece of wood to limit variations in material properties
 470 like density, Young’s modulus, and shear modulus. All the spruce
 471 soundposts of the instruments were made from a single piece of wood for similar reasons. The shape and



The
 the
 made

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

472 size of the bass bar was conventional with a length of 26.7mm, thickness of 5.5mm at its base and height
473 from 13mm at the center on the bridge position towards 3mm at the end. String length from the upper nut
474 to the bridge is a standard 328mm, height of the bridge from the soundboard to the highest point of the
475 bridge was 32-33mm. The strings on all violins were: *Dominant* g (133 medium synthetic core, silver
476 wound), d (132a medium synthetic core, silver wound), a (131 medium synthetic core, aluminum wound)
477 produced by Thomastik-Infeld GmbH © and *Kaplan* e (k420B-3 medium tinned carbon steel core)
478 produced by D'Addario & Company, Inc. ©.



479

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

481 *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

482
 483 Damping measurements are derived from the modal analysis of beams cut along (longitudinal, l)
 484 and across the fibers (transversal, t) through impact excitation in the center of the beam and
 485 response measurement with 3 Polytec PSV 500 laser Doppler vibrometer directed at the left,
 486 middle and right side of the beam respectively (Table IV). Only the quality factor of the first
 487 mode of each beam is provided, which serves as an approximation of the damping properties of
 488 the material. The quality factor Q describes how much energy is lost during the resonating
 489 movement. A vibration with a high quality factor loses less energy over time and therefore has a
 490 lower damping.

491
 492 *Table IV Measured quality factors of beams cut along (l) and across (t) the fibers, from four spruce plates and six composite*
 493 *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

494

495 **Additional information on the sound radiation measurements.**

496 Sound radiation measurements were performed in an anechoic
 497 chamber to reduce noise and the influence of room acoustics. The
 498 violin was mounted on a rig and excited with a miniature impact
 499 hammer (PCB 086E80), acoustic response was measured with a
 500 microphone (DPA 2006-C) at a distance of 33 cm from the bridge.

501 The instrument was measured in 12 positions, with a 30° clockwise
 502 turn of the horizontal plane between each position. The
 503 measurement for each position consisted of 3 excitations, of which
 504 a complex average was calculated. The coherence function was

505 used as a quality parameter, if the coherence was not consistently close to 1 the measurement was
 506 repeated. The entire measurement was performed with both horizontal (on the side of the bridge) and
 507 vertical excitation (on the top of the bridge). The Oberlin Acoustics App (ObieApp1.0b71) was used as
 508 acquisition software, which runs on a LabView platform.



509

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

510 **Additional information on the listening tests.**

511 In the evaluation experiment, the violin player chose to play a modified piece of Symphony Espagnole by
512 Édouard Lalo. In specific she chose part 4, pg 1, and modified it so that each string was played for
513 approximately the same time. The excerpt played was approximately 88 seconds at its longest. All
514 excerpts played were recorded with two Zoom H4N – Neuman microphones (km184NI). One microphone
515 was placed approximately 1m behind the screen, the other approximately 4m further in the room. The
516 recordings are available for other researchers on request, please contact the main author. In the selection
517 experiment, the two violin players first played a 3 octave scale starting from G₃ on each violin (34
518 seconds), followed by an excerpt of their choice from the 9th symphony by Antonin Dvořák (due to
519 practical limitations this experiment could not be recorded).

520 **Additional results of the evaluation experiment:**

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

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

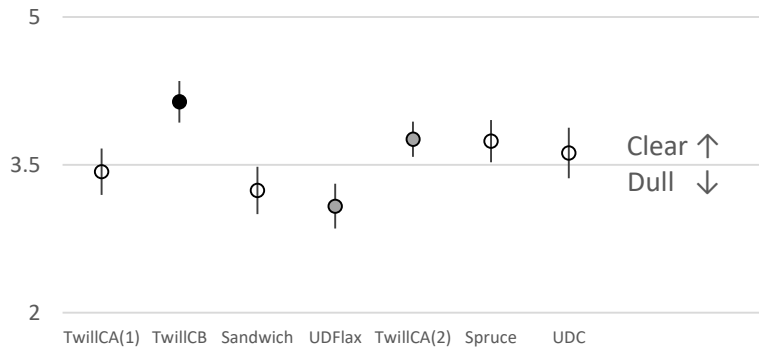
528 **Figures showing the rating of the violins in evaluation task (mean +/-1 standard error of the mean).**

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

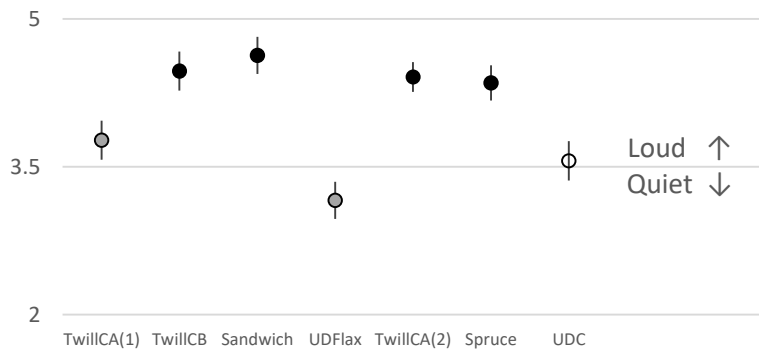
530 Filled yellow dots indicate a weak deviation (p-value<0.1).

531

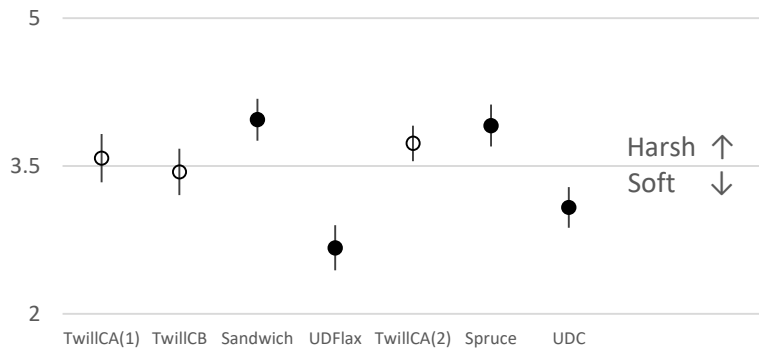
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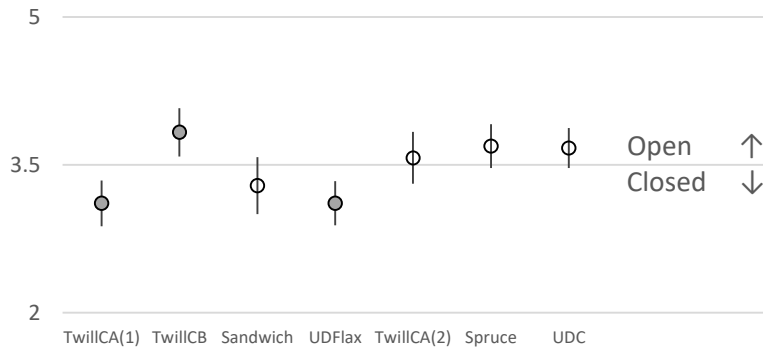


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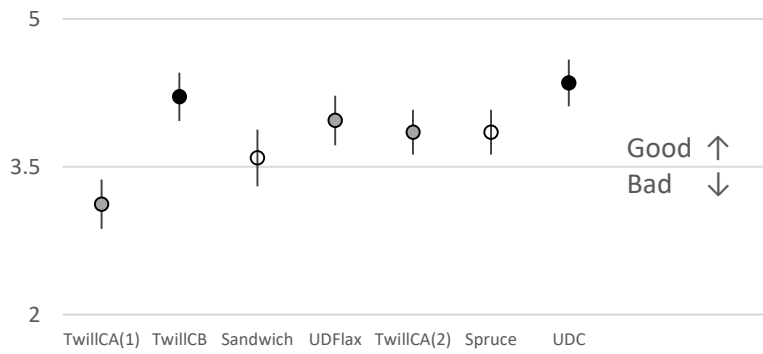


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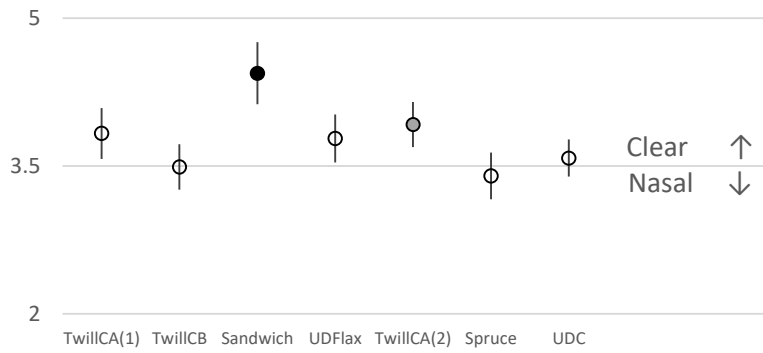




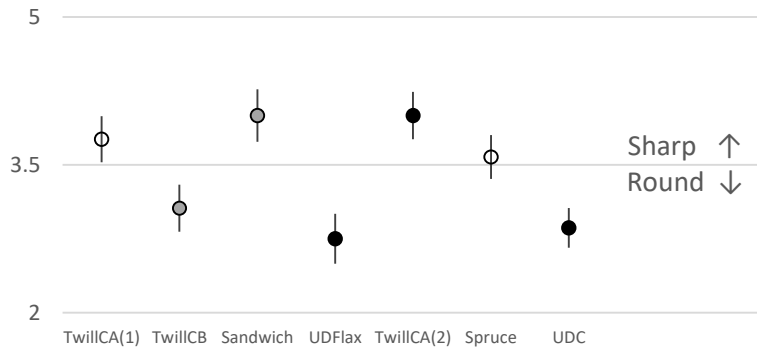
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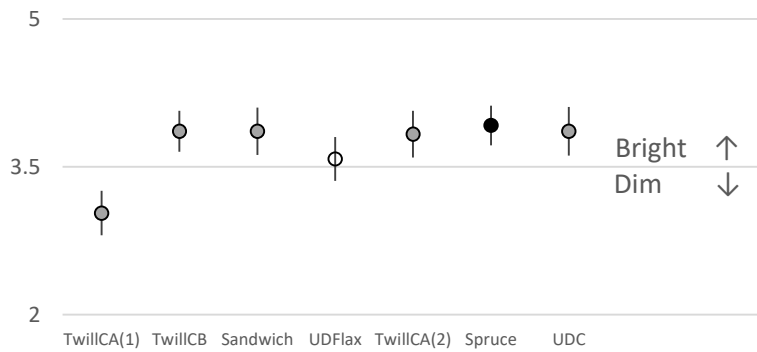


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541

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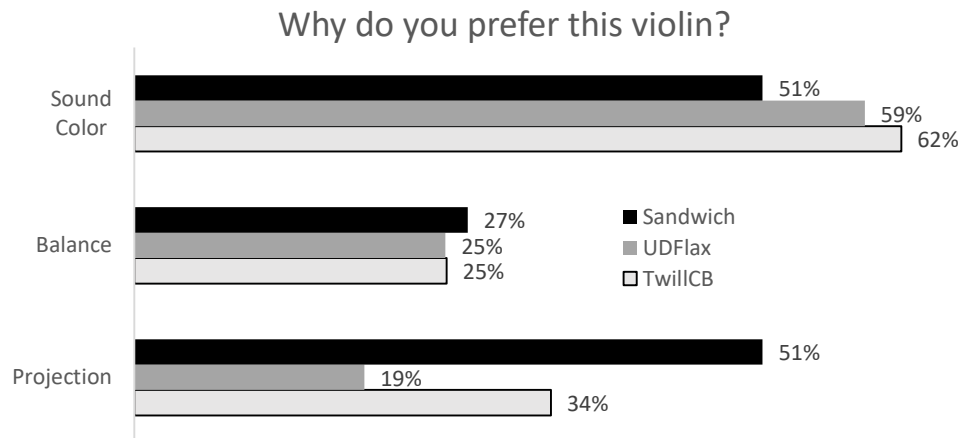
Figure 6: Mean score +/- SEM of the violins on the pairs of adjectives presented on a 8-point Likert scale. Filled black dots indicate a statistically strong deviation (p -value <0.05) from the expected mean (3.5 dotted line). Filled grey dots indicate a statistically weak deviation (p -value <0.1).

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

550 **Additional results of the selection experiment.**

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

554



555

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

557

558

559 **Questionnaire evaluation task:**

560 Dear participant,

561

562 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
563 order. You will listen multiple times to respectively violin 1, 2, 3, 4, 5, 6, and 7.

564 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
565 you. Pay attention! The pages are printed recto-verso. On the last page you will find some general questions about the instruments and your
566 personal background. Please take care to fill in everything, otherwise your contribution can not be used for the research.

567 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
568 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
569 a preference between the two words you select the box 'I don't know'.

570 If you don't understand something or have questions about how to fill out this questionnaire, please ask before the start of the experiment.

571 After the experiment the instruments will be revealed, then there is time and space for questions and discussion. This questionnaire is personal,
572 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.

573 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
574 which more information about the different words is given.

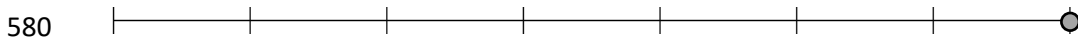
575 Here are some examples on how to fill in the scale using the example of tasting different apple pies.

576

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

578 *Sour* *Sweet* *I don't*

579 *know*

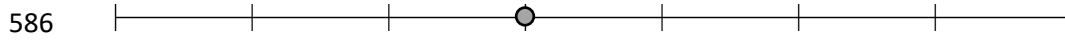


581

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

584 *Sour* *Sweet* *I don't*

585 *know*

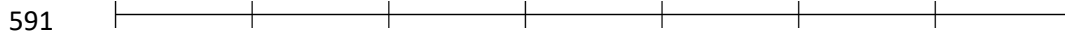


587

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

589 *Sour* *Sweet* *I don't*

590 *know*



592

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

594 somewhere on the scale.

595

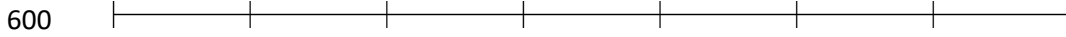
Violin 1

596

597

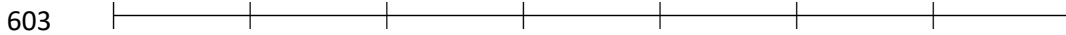
598 Open Closed | don't

599 know



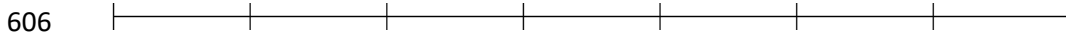
601 Round Sharp | don't

602 know



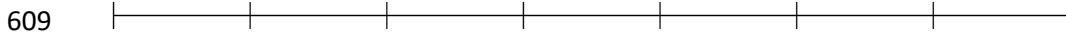
604 Quiet Loud | don't

605 know



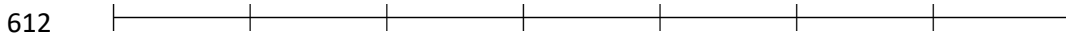
607 Cold Warm | don't

608 know



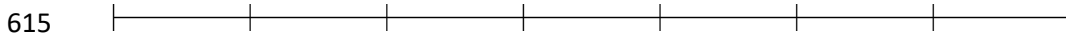
610 Harsh Soft | don't

611 know



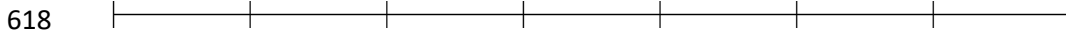
613 Powerful Weak | don't

614 know



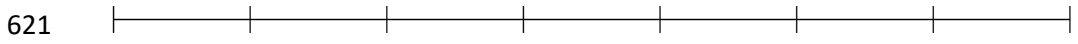
616 Bad Good | don't

617 know



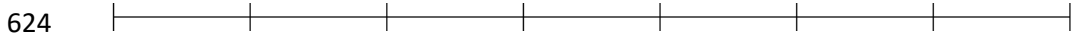
619 Rich Poor I don't

620 know



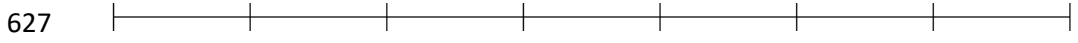
622 Dull Clear I don't

623 know



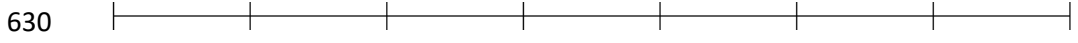
625 Bright Dim I don't

626 know



628 Nasal Clear I don't

629 know



631

632

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

634

635

636 General questions

637

638 The best instrument is in my opinion Nr:

639 The second best instrument is in my opinion Nr:

640 The worst instrument is in my opinion Nr:

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

642 Which instrument did you find most warm sounding?.....

643 Which instrument did you find most powerful sounding?.....

644 Which instrument did you think most rich sounding?.....

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

646

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

648

649

650 If I could take an instrument home I would take Nr:

651

652 Put a circle around what fits best:

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

654

655 Do you regularly play an instrument?

656

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

658

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

660

.....

661

662 **EXPLANATION WORDS SHEET**

663	English:	Dutch:
664		
665	open	open
666	Description: free, loose	Beschrijving: vrij, los
667	Contradiction: closed	Tegenstelling: gesloten
668		
669	loud	luid
670	Description: a great volume in sound.	Beschrijving: een groot volume in klank.
671	Comparison: shouting is loud, whispering is silent.	Vergelijking: Roepen is luid, fluisteren is stil.
672	Contradiction: quiet	Tegenstelling: stil
673		
674	warm	warm
675	Description: with depth.	Beschrijving: met veel diepte.
676	Comparison: some radio-presenters, often on	Vergelijking: sommige radio-presentatoren,
677	late-evening broadcasts, have a very 'warm' voice.	vooral op Klara en in laatavond programma's, hebben een zeer
678		'warme' stem.
679	Contradiction: cold	Tegenstelling: koud
680		
681	clear	helder
682	Description: without noise, lucid, light, pure.	Beschrijving: duidelijk en zonder bijgeluiden, klaar, licht, zuiver.
683	Contradiction: dull	Tegenstelling: dof
684		
685	powerful	krachtig
686	Description: strong, overwhelming, muscled	Beschrijving: sterk, overweldigend, gespierd
687	Contradiction: weak	Tegenstelling: zwak
688		
688	sharp	scherp
689	Description: cutting, pointy, penetrating	Beschrijving: snijdend, puntig, doordringend
690	Contradiction: round	Tegenstelling: rond
691		
692	nasal	nasaal
693	Description: nose sound	Beschrijving: neusklank
694	Comparison: someone who talks with a	Vergelijking: iemand die met een afgesloten neus praat,
695	closed nose, or sound that are carried through	of klanken die door de neus naar buiten worden gedragen
696	the nose like 'n' and 'ng'.	zoals 'n' en 'ng'
697	Tegenstelling: clear	Tegenstelling: helder
698		
699	harsh	hard
700	Description: something that is strongly expressed	Beschrijving: iets dat sterk uitgedrukt of uitgesproken is.
701	or pronounced. Solid and firm.	Vast en stevig.
702	Contradiction: soft	Tegenstelling: zacht
703		
704	rich	rijk
705	Description: with many harmonic overtones,	Beschrijving: veel harmonische boventonen, met een
706	with a broad and full harmonic spectrum.	breed en vol spectrum
707	Contradiction: poor	Tegenstelling: arm
708		
708	bright	briljant
709	Description: with a brilliance, sparkling, virtuoso	Beschrijving: Met een schittering, fonkelend, virtuoos

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

711 **Questionnaire selection task**

712 Dear participant,

713 Thank you for participating in this blind listening test.

714 For each violin player, you will hear six pairs of violins. Please put a circle around the instrument that

715 enjoys your preference and indicate why you chose this violin as favorite. You can select multiple

716 reasons. If you choose Sound color, please describe it by putting a circle around the words that best

717 describe said sound color for you. If you have other words to describe the sound, you can write these on

718 the dotted line.

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

720 be changed between the violin players.

721 If you have any questions regarding this questionnaire please ask them before the start of the

722 experiment. After the test is concluded the instruments will be revealed and there will be time for

723 additional questions.

724

725 What instrument(s) do you play:

726 How many years do you play a musical instrument:

727

728 **Violinist nr. 1**

729 Pair 1:

Violin nr. 1

Violin nr. 2

730 Better projection

731 Better balance

732 Better sound color

warm harsh clear rich open sharp round bright powerful nasal

733

734

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784 Tables

786 *Table I: Weight of the finished soundboards, engineering constants calculated using eLamX² and estimation of damping of the*
 787 *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	-

788
 789 *Table II: Strong and weak evidence to reject the null-hypothesis and link adjectives to the sound of each of the seven investigated*
 790 *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

791
 792 *Table III: Preference of listeners for composite violins when presented in pairs during our selection experiment. The pairs with the*
 793 *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			Sound Color
	listeners	Projection	Balance	
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

794

795

796
797

Figure captions

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

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

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

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

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

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

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