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Effect of back wood choice on the perceived quality of steel-string acoustic guitars

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2 are expensive, rare, and from unsustainable sources. It is unclear to what extent
3 back woods contribute to the sound and playability qualities of acoustic guitars. Six
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13 31 guitarists, indicate that guitarists could not easily distinguish the guitars by their
14 sound or feel. Overall, the results suggest that the species of wood used for the back
15 and sides of a steel-string acoustic guitar has only a marginal impact on its body
16 mode properties and perceived sound.

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17 I. INTRODUCTION

18 A. Back wood in acoustic guitars

19 The acoustic guitar is one of the most popular musical instruments across the world. In
20 the U.S. alone, more than one million acoustic guitars are sold each year ([Music Trades,](#)
21 [2016a](#)). The sound of an acoustic guitar depends in part on the woods used in its construc-
22 tion. It is universally agreed that the top plate is the most important component from this
23 point of view ([Richardson, 1994](#)). However, the attention of guitar players is often focused
24 on the choice of wood used for the back and sides of the soundbox ([Johnston, 2006](#), [2013](#)).
25 For brevity, this will be referred to as the back wood.

26 Unfortunately, many traditionally prized back woods are not only expensive, but also
27 rare and from unsustainable sources. For example, since 1992 Brazilian rosewood (*Dalbergia*
28 *nigra*) has been in Appendix I of the CITES convention, which lists plant species threat-
29 ened with extinction ([Greenberg, 2016](#)). In 2017 the whole *Dalbergia* genus was listed in
30 Appendix II of the CITES convention ([Bedell, 2017](#); [Music Trades, 2016b](#)). The scarcity
31 and increasing cost of many traditional back woods has pushed guitar makers to explore
32 alternative solutions. These have included the use of less familiar species of tropical woods
33 that are more readily available ([Ellis et al., 2008](#)), temperate woods such as maple and wal-
34 nut, laminates ([French and Handy, 2006](#)), and synthetic materials such as carbon fiber or
35 fiberglass composites ([Forbes-Roberts, 2008](#); [Pedgley et al., 2009](#)).

36 Opinions about the acoustical importance of the back wood are widely disparate. The
37 famous maker Antonio de Torres Jurado, usually credited as the originator of the modern

38 classical guitar, was so keen to demonstrate that the back is not very important that he made
39 an instrument with a papier-mâché body ([Romanillos, 1997](#)). Other contemporary luthiers
40 have also played down the importance of back wood choice arguing that within-species
41 wood variability can be at least as big as between-species variation and that in any case the
42 maker has a lot of freedom in constructional details that can be exploited to make excellent
43 sounding instruments with any wood that is structurally suitable ([Gore, 2011](#)). Nonetheless,
44 many guitar makers, dealers, and players have a strongly contrary view, which holds that the
45 back wood makes a significant and immediately obvious difference to the sound of a guitar.
46 Certain tropical hardwoods are highly prized: Brazilian rosewood in particular is often
47 considered the “gold standard” for acoustic guitar backs. There are abundant anecdotal
48 references to this belief in specialized guitar magazines and books ([Bourgeois, 1994](#); [Hunter,](#)
49 [2014](#); [Johnston, 2011](#); [Relph-Knight, 2011](#); [Sandberg and Traum, 2000](#)).

50 When commencing a new instrument, the maker chooses a wood species and then a
51 particular sample of that species. The choice is not determined solely by acoustical consid-
52 erations: visual appearance, ability to take the traditional high-gloss finish, stability and
53 resistance to cracking, working qualities on the bench, and long-term resistance to deforma-
54 tion in response to the static stress from the strings are all important as well. The maker
55 then makes some choices of detailed dimensions (shape, thickness, bracing pattern etc.), and
56 the result is a soundbox with certain vibration modes and associated resonance frequencies
57 and damping factors. These modal parameters give the acoustical ‘fingerprint’ of the in-
58 strument, and determine many aspects of the sound. But the sound is also affected by the

59 player’s choice of strings, and by details of the final set-up by the maker: for example the
60 configuration of bridge saddle and nut, fretting and action height.

61 There has been a considerable amount of research on the acoustic properties of wood
62 (Haines, 1979; Wegst, 2006; Yoshikawa, 2007). However, measurements of the mechanical
63 properties of different wood species are of limited value unless they can be clearly related
64 to the mechanical response of the guitar soundbox, and thence to the acoustical properties,
65 and thence to listeners’ perceptions and preferences (Fritz and Dubois, 2015; McIntyre and
66 Woodhouse, 1978). There is some scientific literature relating to all these stages, reviewed
67 briefly below, but to date there has been no clear synoptic effort to apply rigorous scientific
68 methods to the overall question: ‘does the back wood choice of an acoustic guitar, in itself,
69 produce repeatable and recognisable differences of sound quality?’ That is the main task of
70 this study, to be tackled by a combination of physical measurements and blinded perceptual
71 experiments.

72 **B. Guitar acoustics background**

73 There is a considerable literature relating to the acoustics of the violin, and a somewhat
74 smaller collection relating directly to the guitar. In both cases much emphasis has been
75 placed on understanding a relatively small number of low-frequency modes of vibration: the
76 only ones that an instrument maker can reasonably expect to control in detail (Woodhouse,
77 2002). For the violin, the picture is quite complicated: a clear physical understanding of
78 these low frequency modes has only appeared quite recently (Gough, 2015), and it is also
79 known that some aspects of behavior at much higher frequency are of great perceptual

80 importance. Furthermore, the non-linear nature of a bowed string introduces another layer
81 of complexity into understanding the “tone” of violins ([Woodhouse, 2014](#)).

82 The guitar is much simpler. Any plucked-string instrument is to a good first approxima-
83 tion a linear system, so that understanding the modes of the complete system should contain
84 *all* relevant information. For the guitar specifically, it has been strongly argued that a few
85 low-frequency modes are responsible for the dominant aspects of radiated sound and thus
86 perception ([Richardson, 1994](#); [2002](#)). Furthermore, these low-frequency modes are rather
87 easy to understand in physical terms. The rib structure of a guitar is much more solid than
88 that of a violin, so there is very little deformation of the ribs at low frequency. The top
89 plate behaves largely as if it were clamped along the rib line, as does the back plate. The
90 coupling between the two is mainly through pressure changes in the air inside the cavity,
91 plus some motion of the rib garland as a rigid mass.

92 The result is that the expected influence of the back plate is easy to predict. There is a
93 triad of modes resulting from coupling of a ‘Helmholtz-like’ mode of the air and the lowest
94 modes of the top plate and back plate separately. The other strong low-frequency modes
95 are confined almost entirely to the top plate, with little or no coupling to the air and thus
96 little or no influence of the back plate. So the influence of the back is expected to come
97 mainly through the details of the triad of coupled modes, determined by a combination of
98 the mass of the back and its stiffness in that lowest clamped mode. This mass and stiffness
99 relate directly to things a maker is likely to be able to “feel in the hands” when working on
100 the free back plate ([Christensen and Vistisen, 1980](#); [Fletcher and Rossing, 1998](#); [Richardson,](#)
101 [1994](#); [2002](#)). It follows that a skilled guitar maker might, to a very large extent, be able

102 to compensate for the properties of different back woods by adjusting constructional details
103 such as the thickness of the back plate, to achieve very similar-sounding instruments using
104 different woods.

105 C. Guitar psychoacoustics background

106 Some psychoacoustic experiments have been carried out on guitar sounds ([Woodhouse](#)
107 [et al., 2012](#); [Wright, 1996](#)). Perceptual thresholds have been established when controlled
108 changes are made to the modal properties of the instrument body ([Woodhouse et al., 2012](#)).
109 Most of the results were for nylon-strung guitars, but one would expect these thresholds
110 to be little changed with steel-strung instruments. These studies were based on listening
111 tests using synthesized sounds created from calibrated measurements on real instruments
112 and strings. Related studies have been made for violin sounds ([Fritz et al., 2007](#)). For
113 the guitar, the most acute listeners were able to discriminate a shift of low-frequency body
114 mode frequencies of the order of 1–2%. Listeners were less sensitive to body damping: the
115 Q-factors of body modes needed to be changed by around 20% to be audible.

116 Listening tests based on modal synthesis can provide valuable information on the relative
117 acoustic discriminability of changes in different physical parameters of musical instruments.
118 However, the absolute discriminability measured with such listening tests may not tell the
119 whole story in relation to playing tests performed in a musical context. There are many
120 complicating factors: for example interactions between the player and the instrument that
121 are only present in playing tests ([Fritz and Dubois, 2015](#)), the effect of variability in players’
122 performance, and differences in the test conditions.

123 Characterizations and comparisons of different woods based on players' perceptions and
124 preferences abound in guitar magazines and online forums. However, these subjective char-
125 acterizations and comparisons are rarely (if ever) done under blinded conditions. As a result
126 they may be severely biased by a variety of factors including prejudice for or against certain
127 wood species, visual aesthetics, and price. The impact that such biases can have has been
128 illustrated by a series of studies on players' preferences among modern and old violins ([Fritz](#)
129 *et al.*, 2014; 2012). In these studies, conducted under blinded conditions, expert violinists
130 showed a slight but distinct tendency to prefer certain high-quality contemporary violins
131 over old Italian violins made by Stradivari and Guarneri, despite the fact that the old in-
132 struments are generally regarded by experts as being tonally superior and are typically worth
133 many times more than the best contemporary violins. To the best of our knowledge no pub-
134 lished studies have ever compared, using a blind test methodology, players' preferences or
135 discrimination abilities between steel-string acoustic guitars built with different back woods.
136 An unpublished study on classical guitars built with various tropical and non-tropical woods
137 failed to find differences in guitarists' preferences for one type of wood over the other in blind
138 testing sessions ([Walraet and Garston, 2015](#)).

139 **D. Overview of the current study**

140 For the current study, a very experienced luthier (who is the second author of this paper)
141 built six steel-string acoustic guitars to the same dimensional and material specifications of
142 all their parts, except for the back and side plates, which used different woods ranging widely
143 in mechanical properties, popularity among players, and price. Different back wood species

144 are normally worked differently according to their mechanical properties, and this standard
145 practice was followed in the current study. The typical working thickness for back plates
146 and sides ranges from around 2 to 2.8 mm for different timbers. Sides made from denser
147 timbers, like those in the rosewood family, become very difficult to bend at 2.8 mm, to the
148 point of impossibility on sharp curves. Conversely, less dense woods such as mahogany and
149 walnut are intrinsically weaker, and would be far too fragile if worked to 2 mm thickness
150 over the width of a back, typically 200 mm, or the depth of the sides, typically 100 mm.
151 It should be also pointed out that these thicknesses are starting points: after the initial
152 thickening of the sides, then bending, most wood will distort from the heat and moisture,
153 and must be levelled off over a width of around 100 mm, so it is not uncommon to have
154 wood only about 1 mm thick in some places. This is not a concern if it occurs near an edge,
155 but requires reinforcement if it occurs in the middle of a side. For all these reasons it would
156 not be desirable or even possible to work different timbers to identical thickness.

157 For the reasons discussed above, the back and side plates of the six guitars differed
158 not only for the wood species used but also in their detailed thickness distribution. It is
159 important to emphasize that this is a strength, not a weakness, of the study. To ask “do
160 guitars sound different if different back woods are used with identical thickness?” would not
161 be an interesting research question, because no professional instrument maker would ever
162 do this. The aim is to ask whether other woods can be used as a satisfactory substitute
163 for Brazilian rosewood and other traditional choices, by experienced luthiers who make the
164 best use of each alternative wood. For brevity in this paper we will refer to the combined

165 differences in back wood species and in their dimensional specifications as “back wood”
166 differences.

167 Experienced guitar players were asked to rate the six guitars on a series of perceptual
168 attributes, including an “overall sound” quality rating. A subset of players was tested twice
169 to assess the consistency of their ratings. The players’ ability to tell apart two different
170 guitars was also assessed for three of the guitars using an objective ABX testing methodology.
171 Both the rating and ABX tests were carried out in a dimly lit room with the players wearing
172 welder’s goggles that allowed them to see the position of their fingers on the fingerboard,
173 but prevented them from recognizing the back wood.

174 The guitars were also tested to establish some physical acoustical parameters. The bridge
175 admittance was measured, which allows body mode properties to be extracted. The results
176 can be combined with the earlier threshold data to predict the discriminability of any given
177 pair of guitars. Those predictions were compared with the results of the playing tests
178 described above. As a further step, short passages of music were synthesized using the
179 measured modal properties. Those synthesized sounds were used in another series of ABX
180 listening trials to test directly for the influence of modal frequencies, while controlling for
181 other factors such as variability in player’s performance.

182 II. GUITAR BUILDING PROCESS

183 Six steel-string acoustic guitars were hand-built at the workshop of Fylde Guitars (Pen-
184 rith, UK), on commission for the experiment. The guitars were all based on the “Falstaff”

185 model, which has a relatively large body (see Table S1 in the supplementary material¹ for
186 dimensional specifications). A design with a two-piece back was used for the current study.

187 The top plates of all the guitars were made of Sitka Spruce (*Picea sitchensis*) taken from
188 a single flitch of timber. Four of the plates were consecutive cuts from the same log. It was
189 not possible to obtain six consecutive cuts, but all the chosen plates were manually matched
190 for stiffness and weight, and for similar grain spacing and pattern. The necks were cut from
191 one plank, as were the internal braces. The fingerboards and bridges were Cameroon ebony
192 (*Diospyros crassiflora*). The component parts were worked exactly in parallel so that, for
193 instance, the thickness of each top plate and each brace was determined using the same
194 settings and at the same time. The brace shaping and neck shaping were done by hand, but
195 with significant effort to keep them the same. Any gluing operation was performed as much
196 as possible in parallel, using the same pressure, the same gluing time, and the same ambient
197 temperature. A particular effort was put into matching the neck angle and string height.

198 The woods for the back and side plates were chosen to be representative of timbers
199 commonly used in acoustic guitar making and to cover a wide range of price and avail-
200 ability (see Table S2 in supplementary material), they were: Brazilian rosewood, Indian
201 rosewood (*Dalbergia latifolia*), South American mahogany (*Swietenia macrophylla*), sapele
202 (*Entandrophragma cylindricum*), North American maple (*Acer macrophyllum*), and North
203 American claro walnut (*Juglans hindsii*). The specific pieces of timber were chosen as being
204 representative of that species, taking weight and stiffness as the most important parameters.
205 Physical appearance was not a factor in the selection process. As already mentioned, the
206 back and side plates were not built to identical dimensional specifications. Instead, each

207 guitar was made exactly as if it were a standard order for a customer. The thickness of the
208 back and side plates were individually adjusted according to the properties and “feel” of
209 each one.

210 Different timbers also require different finishing schedules, because of variations in grain,
211 but considerable effort was made to keep the finish balanced. No filler was used. Each
212 guitar was sprayed with polyurethane lacquer and rubbed back until the grain was “just”
213 full and level. Equal spray coats were then applied, levelled and polished so that the coating
214 thickness was equal on each instrument. Each guitar was set up to similar measurements
215 and monitored for about six weeks, then readjusted before the first tests. The guitars were
216 fitted with Elixir Nanoweb Light Acoustic 80/20 Bronze strings (W. L. Gore & Associates,
217 Inc., Newark, DE), which were changed twice over the course of the experiments on all
218 guitars at the same time, including just before the bridge admittance measurements.

219 **III. PHYSICAL MEASUREMENTS**

220 **A. Bridge admittance and modal parameters**

221 The input admittance at the bridge of each guitar was measured by applying a controlled
222 force via a miniature impulse hammer (PCB 086D80) in the direction normal to the plane of
223 the top plate, and measuring the velocity response with a laser-Doppler vibrometer (Polytec
224 OFV-056). The measurement point was on the bridge saddle between the 5th and 6th string.
225 The strings were damped, and the instruments were supported in a vertical position with

226 soft foam at the end button and a foam-lined clamp on the neck. Further details have been
227 described by [Woodhouse and Langley \(2012\)](#).

228 The results for each guitar are shown in Fig. 1A, alongside those of a different steel-string
229 acoustic guitar, a Yamaha FG-403MS (Yamaha Corporation, Hamamatsu, Japan) that was
230 not part of the experimental set of guitars. It is immediately clear that all guitars have three
231 strong peaks at low frequencies, after which the behavior settles into a relatively smooth
232 and lower-level trace at higher frequencies. The three strong peaks were used in listening
233 tests reported in Section [VII](#), and their modal frequencies and damping factors are listed
234 in Table [I](#). The interpretation of these three modes is as follows: the first two are part of
235 the coupled triad discussed earlier, while the third peak is a transverse bending mode of
236 the top plate. The first two are significantly influenced by the back, while the third one
237 should have only a very weak influence from the back: its frequency is determined mainly by
238 the transverse stiffness of the top plate, including the effect of the wood, thickness, bracing
239 and bridge ([Christensen and Vistisen, 1980](#); [Fletcher and Rossing, 1998](#); [Richardson, 1994](#),
240 [2002](#)).

241 Figure 1B shows resynthesized bridge admittances corresponding to the subset of the
242 guitars used in the tests to be described in Section [VII](#). The Yamaha guitar has been used
243 as a reference case, because a detailed modal fit up to 1200 Hz was available for this guitar.
244 Modified versions were then computed in which the low-frequency modal properties were
245 replaced with the measured values from the set of guitars, given in Table [I](#). The resulting
246 pattern is clear in the figure: in each case the low-frequency behavior is a close match
247 to the measured response of the chosen guitar, while the response at higher frequencies is

248 essentially identical in all cases (and includes no modes above 1200 Hz). It would, of course,
249 be virtually impossible to achieve this kind of controlled variation of modal properties with
250 physical instruments.

251 B. Wood properties

252 It is useful to have some idea of the physical properties of the different woods used in this
253 study. For logistical reasons it was not possible to test the particular specimens used to build
254 the six guitars, but two examples of each wood type were selected for testing from the wood
255 store of the same luthier. Back-plate blanks were thickened and shaped to rectangular
256 form, then tested by the procedure described in [McIntyre and Woodhouse \(1988\)](#). Since the
257 wood was intended for two-piece backs, the two halves from each set could be independently
258 tested to give a direct measure of the consistency of results for samples of wood that are as
259 similar as possible.

260 The measurements yield density, plus three stiffnesses called D_1 , D_3 and D_4 by [McIntyre](#)
261 [and Woodhouse \(1988\)](#). D_1 and D_3 quantify the long-grain stiffness and cross-grain stiffness,
262 while D_4 quantifies the twisting stiffness. A fourth stiffness, D_2 , relates to Poisson's ratio:
263 it is more difficult to measure, but it has little influence on the vibration behavior of the
264 plates and so it is ignored here. It is a deliberate choice to present results for the unfamiliar
265 D_j rather than the more familiar Young's modulus, shear modulus and so on. These more
266 familiar moduli can only properly be regarded as properties of the solid wood, whereas the
267 D_j are properties of the actual plate as cut from the solid wood. The values are sensitively

268 influenced by the way the wooden plates have been cut from the log as well as by the
269 underlying wood properties: see [McIntyre and Woodhouse \(1988\)](#) for details.

270 The results are plotted in Figure 2. In all cases, the pairs of symbols indicating the two
271 halves of a given set of wood fall reassuringly close together. The density results show that
272 the four non-rosewood timbers have rather similar densities: the between-species variation
273 is no bigger than the within-species variation shown by the pairs of tested sets. For the
274 stiffnesses, Brazilian rosewood generally shows the highest values, while walnut shows the
275 lowest. In most cases the results for the two tested sets of each wood fall close together.
276 The conspicuous exceptions come from the values of D_3 for mahogany and sapele: in both
277 cases one set shows much lower values of this cross-grain stiffness. The difference is mainly
278 attributable to the fact that the low values are associated with samples that have been cut
279 a long way off the quarter.

280 C. Discussion

281 The measured bridge admittances and deduced modal properties show subtle differences
282 between the guitars. However, careful examination of the results suggests that the differences
283 seen were *not* caused primarily by the choice of back wood. Despite best efforts to vary only
284 the back wood and keep other variables constant, the subtle variations observed between
285 the guitars are probably due to small differences in the top plates (with bridge, bracing
286 and lacquer) rather than to the deliberate differences in back woods. The evidence for this
287 suggestion is that the frequency F_3 — which should essentially be independent of the back

288 — in Table I shows variations at least as big as those in the other two low modes, and
289 furthermore the three frequencies show strong correlation.

290 The guitars made with Indian rosewood and sapele show the most extreme differences:
291 frequencies that are systematically sharp and flat, respectively, by about half a semitone
292 compared to the mean of the set, so that relative to one another they show about a semitone
293 difference. But these are not the woods that stand out as extreme on the basis of the
294 measured wood properties shown in Fig. 2: Brazilian rosewood is both the densest and the
295 stiffest, while walnut is probably at the other extreme.

296 These observations have two important consequences. First, the similarity of the re-
297 sponses despite the very different properties of the back woods confirms a possibility men-
298 tioned earlier. The guitar maker, by treating each back plate in the way that his experience
299 suggested was best, has to a very large extent compensated for any physical differences be-
300 tween the types of wood. The biggest residual difference in acoustical behavior is between
301 guitars built with two woods that were not judged to be the most extremely different from
302 the maker’s perspective (sapele and Indian rosewood). The guitar made with Brazilian
303 rosewood, traditionally the favoured back wood, does not stand out in these results. Its
304 acoustical response and modal properties fall in the middle of the range on all measures,
305 specifically appearing to be rather close to the sapele instrument.

306 The second consequence is a prediction about perceptual discrimination between the
307 guitars in the set. The thresholds found in earlier work ([Woodhouse *et al.*, 2012](#)) suggest
308 that the sapele and Indian rosewood guitars should be sufficiently different in their low modal
309 frequencies that a skilled listener would be able to tell them apart moderately reliably. But

310 these are the extremes of the range, and all other pairs of guitars would be predicted to be
311 hard to discriminate.

312 However, one should be cautious about generalizing predictions derived from absolute
313 thresholds obtained in listening tests with synthesized sounds to real-life playing tests. On
314 the one hand musical perception is subtle and context-dependent. It is possible that experi-
315 enced musicians playing real instruments might be more discriminating than is suggested by
316 these predictions, based as they were on very artificial listening conditions with headphones
317 and synthesized sound fragments. On the other hand, it is possible that the constraints of
318 real-life playing tests, such as variability in player’s performance and delays between listen-
319 ing of two guitars due to the need to physically swap instruments, may make discrimination
320 more challenging in these tests. The remainder of this paper presents the results of a variety
321 of psychoacoustic tests using the guitars of the test set, to explore these possibilities.

322 IV. PSYCHOACOUSTICS EXPERIMENTS METHODOLOGY

323 A. Participants

324 Fifty-three guitar players took part in one or more experiments in the study. The par-
325 ticipants were not screened for hearing loss, but two participants reported a diagnosis of
326 hearing loss. One of these two participants reported a moderate hearing loss for both ears
327 and his data were excluded from all analyses. The other participant was profoundly deaf
328 in one ear since childhood; because his self-reported hearing was good for the other ear his
329 data were not excluded from the analyses. The remaining 52 participants (51 males) had a

330 mean age of 42 years (SD=16). They were classified according to their employment status
331 as professional (if they worked full time as guitar players, e.g. artist, guitar instructor, etc.),
332 semi-pro (if they worked part-time as guitar players), or amateur. On average, the players
333 reported having 26 years (SD=15) of experience playing the guitar (30 years for the pro-
334 fessionals, 25 years for the semi-pros, and 25 years for the amateurs). Fifteen participants
335 performed the blinded sound rating test at the Ullapool (Scotland, UK) guitar festival in
336 a large room normally used as a dance studio. All the other participants were tested in a
337 medium-sized furnished room at Lancaster University. Participants were compensated for
338 their time at a rate of £10 per hour.

339 **B. Blinded tests procedures**

340 Participants were tested while wearing welder’s goggles in a dimly-lit room. These test
341 conditions allowed them to see their fingers and the guitar neck while playing, but prevented
342 them from visually identifying the wood of the guitar. To further limit the possibility that
343 participants could recognize the guitars by non-acoustic cues, they were asked to close their
344 eyes both while being handed each guitar by the experimenter, and when the experimenter
345 picked up each guitar from them; they were also asked not to look at the body of the
346 guitars during the test, and not to tap on the guitar body or inspect it in any other way.
347 The lacquer on the guitars substantially eliminated possible odor cues that could make the
348 different woods recognizable. Nonetheless, an air freshener placed on a table close to the
349 player was used to mask any potential residual odor cues.

C. Statistical analyses

Statistical analyses were performed using Bayesian general linear models (GLM) implemented with Markov Chain Monte Carlo (MCMC) methods (Kruschke, 2014). Details of the models are provided in the supplementary material. Because MCMC methods are stochastic their results can vary slightly on different runs. For this reason, as well as to avoid rejecting a given null hypothesis on the basis of a trivial effect size, we only rejected a null hypothesis for differences whose 95% credibility intervals (CIs) fell outside a region of practical equivalence (ROPE) around the null value (Kruschke, 2014). We will refer to such differences as *credible* differences. For all the measures used in this study the ROPE was set at ± 0.2 because a magnitude of 0.2 represents a very small difference for the rating measures (5% of the scale range), for standardized measures (test-retest correlations and factor scores) and for d' values. These ROPEs could be considered arbitrary, and sometimes the ROPE is not stated explicitly but left to the reader to decide. In practice, the vast majority of the conclusions in our analyses would not be affected by the choice of a different ROPE because most CIs crossed the null value, and therefore could not exceed the criterion for the rejection of the null hypothesis under any choice of ROPE.

V. PSYCHOACOUSTICS EXPERIMENT 1: GUITAR RATINGS

A. Method

Fifty-two guitar players (18 professional, 21 semi-pro, 13 amateur) performed the blinded rating experiment once. A subset of these players (eight professional, 17 semi-pro, nine ama-

370 teur) performed it twice, so that the consistency of their ratings could be assessed. Guitarists
371 played each guitar and were then asked to evaluate it on a 1-to-5 scale for “overall sound”,
372 playability, and 14 additional perceptual attributes listed in Table II. These additional per-
373 ceptual attributes were chosen on the basis of a corpus analysis of online guitar reviews
374 (described in the supplementary material), as well as consultation with the luthier. Some
375 of the resulting rating attributes are likely to be semantically overlapping and thus redun-
376 dant. However, it is not clear how players use these terms to describe the sound of a guitar.
377 Instead of making a priori assumptions on how the terms relate to each other for guitarists,
378 and arbitrarily select one among several possibly related terms to reduce the dimensionality
379 of the dataset, a relatively large number of rating attributes was used at the data collection
380 stage. The dimensionality of the dataset was reduced at the data analysis stage by means
381 of an exploratory factor analysis (EFA), which is described in Section VD.

382 Players were informed that the rating attributes were selected on the basis of a linguistic
383 analysis of guitar reviews and that some attributes may semantically overlap with each other.
384 Although the number of attributes that players had to rate was somewhat higher than in
385 previous studies of players evaluations of musical instruments (Fritz *et al.*, 2014; Saitis
386 *et al.*, 2012), the fact that several attributes were probably semantically related should
387 have considerably reduced the cognitive load needed to perform the task. The order of
388 presentation of the guitars was randomly assigned by a computer algorithm for each player.
389 The experimenter passed each guitar to the player by positioning it directly on the legs of
390 the player. Players were allowed two minutes to play freely with each guitar any tune of
391 their choice. They were allowed to use either a fingerpicking technique, or a pick, and to

392 use a non-standard tuning if they wished. Once the two minutes of free play with a given
393 guitar had elapsed the participants were asked to start the rating phase. They were allowed
394 to keep the guitar during the rating phase and play it again as they wished in order to
395 accurately rate the guitar on each attribute. There was no time limit for this rating phase;
396 most participants completed it in about four to five minutes. For the ratings participants
397 were presented with the 16 questions listed in Table II on the computer monitor, and were
398 asked to answer each question with a 1-to-5 rating by dragging a slider through a mouse.
399 The questions were presented in the same order shown in the table. Non-integer ratings up
400 to one decimal place were allowed (e.g. 3.2). For participants who scored the guitars twice
401 the whole procedure was repeated after a short (5–10 min) break. The total duration of the
402 session for participants scoring each guitar twice was 90 minutes.

403 **B. Results: rating differences**

404 The average “overall sound” ratings given to each guitar are shown in Fig. 3. To estimate
405 the rating differences between guitars in the general population of guitar players, the ratings
406 were modeled by a Bayesian GLM as a function of guitar back wood, player professional
407 status, and individual player (see supplementary material for details). Figure 4 shows the
408 estimates of the rating differences given by the model (filled symbols) alongside their 95%
409 CIs, denoted by the horizontal segments. The estimated differences between guitars were
410 all small (< 0.2). All of the 95% CIs crossed a difference of zero, indicating that none of
411 the differences was credibly different from zero. Moreover, the CIs were relatively narrow;
412 most of them did not exceed a difference of ± 0.3 (7.5% of the scale range), suggesting that

413 even if rating differences between guitars existed in the general population of guitar players,
414 they would be at best small. A qualitatively similar pattern of results was observed for each
415 player category (see Fig. S1A in supplementary material).

416 Because for practical reasons only one guitar of each back wood species could be tested
417 in our experiment, specific comparisons between the individual guitars in our sample are
418 of limited interest: The results strictly apply only to the exemplars tested and because of
419 potential nuisance factors such as within-species variability in the quality of wood, or residual
420 manufacturing variability, may not readily generalize to other guitars of the same species.
421 However, the six guitars tested can be seen as a sample of a population of guitars (from the
422 same maker) nominally differing only in their back woods. The variance in “overall sound”
423 ratings between guitars of this “superpopulation” (Gelman and Hill, 2007) was estimated by
424 our Bayesian model to be low. In standard deviation units its posterior mode was 0.06 with
425 a 95% CI of 0.001 – 0.249. In other words, our results indicate that typical differences in
426 “overall sound” ratings between guitars nominally differing only in their back woods would
427 be in the range of 0.001 to 0.249 (between 0.02% and 6.2% of the scale range). If back
428 woods were a major determinant of a guitar sound, it is very unlikely that in a sample of
429 six guitars taken from that population, all six would be given very similar ratings.

430 Figure 3 shows the average playability ratings given to each guitar. Figure 4 shows
431 the estimates of the rating differences given by the model (filled symbols), and their 95%
432 CIs (horizontal segments). As for the “overall sound” ratings, the estimated differences
433 in playability ratings were small. None of them was credibly different from zero, and the
434 uncertainty of the estimates provided by the CIs suggests that even if rating differences

435 between guitars existed in the general population of guitar players, they would be at best
436 small. Qualitatively, a similar pattern of results was observed for each player category (see
437 Fig. S1B in supplementary material). The superpopulation standard deviation of playability
438 ratings between guitars was estimated to be 0.05 (95% CI: 0.001 – 0.195).

439 **C. Results: test-retest correlations**

440 Figure S2 in the supplementary material shows the ratings given in each session by
441 players who performed the blinded rating experiment twice. We used a Bayesian model to
442 estimate the test-retest correlation for each individual player, as well as at the group level
443 (see supplementary material for details). At the group level this correlation was 0.11, with
444 a 95% CI ranging from -0.04 to 0.26. Hence, the group-level estimate of the test-retest
445 correlation was not credibly different from zero, and taking into account the uncertainty
446 of the estimate provided by the CI, it could be at most around 0.26, which would still
447 indicate poor test-retest consistency of the “overall sound” ratings. The group-level test-
448 retest correlation for the playability ratings estimated by the model was also low, 0.08, with
449 a 95% CI ranging from -0.05 to 0.25.

450 **D. Results: exploratory factor analysis of rating attributes**

451 The ratings given by guitarists on the additional 14 perceptual attributes were entered
452 into an EFA. The purpose of this EFA was to reduce the dimensionality of the dataset,
453 and to define some of the basic perceptual dimensions that are used by guitar players to
454 judge the sound of a guitar. The EFA revealed three orthogonal factors that gravitate re-

455 spectively around the dimensions of loudness, warmth, and clarity (see Fig. S3 and results
456 section in supplementary material). In order to understand how the ratings on these per-
457 ceptual dimensions relate to “overall sound” ratings, we extracted factor scores using the
458 Anderson-Rubin algorithm (DiStefano *et al.*, 2009). A Bayesian multiple regression model
459 (see supplementary material for details), predicting the “overall sound” ratings from the
460 extracted factor scores, indicated that all three factors are credible predictors of “overall
461 sound” ratings. The estimated slope coefficients, which represent the “overall sound” rating
462 change for a unit change in factor score were 0.31 (CI: 0.26 – 0.37) for factor “loudness”,
463 0.35 (CI: 0.29 – 0.41) for factor “warmth”, and 0.42 (CI: 0.37 – 0.47) for factor “clarity”.
464 None of the slopes was credibly different from each other (see supplementary material for
465 details).

466 The extracted factor scores were also used to test statistically whether the guitars differed
467 from each other on these underlying dimensions. This analysis was performed using the
468 same model used for analyzing “overall sound” and playability differences between guitars.
469 The results did not show any credible differences between any pair of guitars for any of
470 the factors (see Fig. S4 in supplementary material). However, there were trends for small
471 differences between some guitar pairs in factor “loudness” and factor “warmth”, and given
472 the relatively large width of the CIs it is not possible to exclude the possibility that small or
473 modest differences between guitars in these factors exist but could not be detected by our
474 measurements.

475 VI. PSYCHOACOUSTICS EXPERIMENT 2: ABX TEST

476 A. Rationale

477 While overall sound quality ratings can provide information on the preferences of gui-
478 tarists for different woods, they cannot determine whether guitarists can perceive acoustic
479 differences between woods. It is possible that guitarists may be able to clearly hear or feel
480 differences between back woods, but have no preference for one over the other. The ABX
481 test is a simple discrimination test that is widely used in the audio engineering community
482 to check whether there are audible differences between sounds ([Boley and Lester, 2009](#)).
483 The simplicity of this test derives from the fact that it only requires the observer to respond
484 on the basis of the perceived similarity between stimuli without the need to have a defined
485 verbal/semantic characterization of the dimension(s) along which the stimuli differ ([Hautus
486 and Meng, 2002](#)). In experiment 2 we used an ABX test to assess the ability of guitar players
487 to discriminate between pairs of guitars by acoustic cues alone.

488 B. Method

489 Thirty-one of the guitarists (seven professional, 14 semi-pro, 10 amateur) who performed
490 the blinded acoustic rating test also took part in an ABX discrimination test. On each trial
491 of this test guitarists played under blinded conditions first one guitar (guitar *A*) for one
492 minute, then another guitar (guitar *B*) for another minute. They were then given again
493 one of the two guitars (guitar *X*), and were asked to decide if it was guitar *A*, or guitar
494 *B*. Because of time limitations only three guitars (Brazilian rosewood, sapele, and walnut)

495 were used in this test. These three woods were chosen among the set of six woods to be
496 representative of different levels of sustainability and price (Table S2), and based on the
497 luthier’s expectations of which woods would be more and less similar. Note from Fig. 2
498 that this selection does indeed include the woods with most disparate physical properties
499 (Brazilian rosewood and walnut).

500 On each trial two of these three guitars were used. The participant was first given one
501 guitar (guitar *A*) to play, and was then given the other guitar (guitar *B*). The participant
502 could request to swap between guitar *A* and *B* as many times as s/he wished within a
503 maximum time period of two minutes (most participants played guitar *A* for one minute,
504 and then guitar *B* for another minute). At the end of the two-minutes period the participant
505 was then given again one of the two guitars (guitar *X*) to play for a minute and was
506 asked to report whether this guitar was guitar *A* or guitar *B*. The three guitars were all
507 tuned to the same nominal pitch prior to the beginning of a session. However, participants
508 could potentially hear residual tuning differences and use them to discriminate between two
509 guitars. In order to avoid this issue, guitar *X* was quickly de-tuned and re-tuned to the
510 same pitch with a digital tuner (Korg AW-2G Clip-On Tuner) by the experimenter before
511 it was handed to the participant. This procedure lasted about 30 seconds. To minimize any
512 possible distraction due to the re-tuning procedure, during this procedure the participant
513 listened to pink noise played at a comfortable level through headphones.

514 The ABX test was completed in two 1-hour sessions that were run on different days. In
515 each session, the players completed four trials for each guitar pair, one for each of the possible
516 ABX stimulus sequences (correct response *A*: $\langle S_1 S_2 S_1 \rangle$, $\langle S_2 S_1 S_2 \rangle$; correct response *B*:

517 $\langle S_1 S_2 S_2 \rangle$, $\langle S_2 S_1 S_1 \rangle$). One of the players was unable to attend the second ABX session,
518 therefore only four trials per guitar pair are available for this player. A roving design
519 was adopted: on each trial both the guitar pair and the stimulus sequence were randomly
520 sampled without replacement from the set of the 12 possible combinations of guitar pairs
521 and stimulus sequences by a computer algorithm. No immediate feedback was given to the
522 participants upon completion of a trial. However, participants were informed of the total
523 number of correct responses at the end of each session. The d' values were computed from
524 hit rates (proportion of times guitar X was correctly identified as guitar A) and false alarm
525 rates (proportion of times guitar X was incorrectly identified as guitar A) assuming that
526 guitarists used a differencing strategy to perform the ABX task (Macmillan and Creelman,
527 2004). This assumption is motivated by the fact that the experiment had a roving design
528 in which the guitar pair for each trial was randomly chosen among the three possible guitar
529 pairs. To avoid undefined values of d' , hit and false alarm rates of 0 and 1 were converted
530 to $1/(2N)$ and $1 - 1/(2N)$, respectively (Macmillan and Creelman, 2004).

531 C. Results

532 Figure 5 shows the average performance in the task for each guitar pair as a function of
533 player professional status. Although there was some variability between player categories,
534 it is evident that d' values were very low overall (a d' value lower than 1 indicates poor dis-
535 criminability). These d' values were modeled as a function of guitar pair, player professional
536 status, and individual player, using a Bayesian GLM (see supplementary material for de-
537 tails). The d' CIs for each guitar pair as a function of player professional status are shown in

538 Fig. 6. When considering the scores across all guitar pairs and player categories the results
 539 show that, although performance was credibly above chance, it was poor, with the 95% CI
 540 for d' falling entirely below 1 (CI: 0.21 – 0.8). Discriminability was not credibly different
 541 between the three guitar pairs tested (see Fig. S5 in supplementary material). There were
 542 trends for professional and amateur players to perform better than semi-pro players, but
 543 these differences were not credibly different from zero (see Fig. S6 in supplementary mate-
 544 rial). It should also be noted that these trends are not entirely in the expected direction, as
 545 one would not expect amateur players to perform better than semi-pro players. However,
 546 this odd trend is consistent with random sampling variability, rather than with a real per-
 547 formance advantage of amateur over semi-pro players. Interactions between player category
 548 and guitar pair were not credibly different from zero.

549 VII. PSYCHOACOUSTICS EXPERIMENT 3: ABX TEST WITH SYNTHESIZED GUITARS

551 A. Rationale

552 In the ABX test described in Section VI it was difficult to implement a control condition
 553 to check that players would perform it well when comparing guitars differing not only in their
 554 back woods but also in other component materials and dimensional specifications. A guitar of
 555 a different size, for example, could have been discriminated just by touch even without being
 556 played. For this reason, a subset of guitar players performed an additional ABX task in which
 557 the stimuli were sounds synthesized on the basis of the bridge admittance measurements of

558 the guitars described in Section III. This allowed us to include a condition comparing one of
559 the six guitars built for the study with a guitar of a different make and model that should
560 have been easy to discriminate. Additionally, the results of this test could be more directly
561 compared with previously published threshold data for changes to the modal properties of
562 the instrument body obtained with synthesized guitar sounds (Woodhouse *et al.*, 2012).
563 We used the same synthesis model of Woodhouse *et al.* (2012), which allows an accurate
564 representation of the coupled mechanical vibration of the strings and guitar body.

565 The musical excerpt chosen as stimulus consisted of the first two measures of the song
566 “Tears in Heaven”. This excerpt was chosen as being typical of fingerpicking acoustic guitar
567 style and for covering a relatively wide register of notes. The same three guitars that were
568 tested in the previous ABX test were again tested. In addition, discrimination performance
569 was assessed between the Indian rosewood and the sapele guitars, because these two guitars
570 have, among the set of the six guitars built for the study, the most disparate modal fre-
571 quencies. Based on the earlier threshold tests (Woodhouse *et al.*, 2012), this pair would be
572 predicted to be the most readily discriminable. Finally, discrimination performance between
573 one of the six guitars built for the study (Indian rosewood) and a guitar of a completely
574 different make and model (Yamaha FG-403MS) was also assessed to check that when the
575 guitars differed not only in their back woods, but also in other characteristics, the ABX test
576 could be performed proficiently by the players.

577 **B. Method**

578 Seven guitarists (three professional, four semi-pro), who had previously taken part in
579 both experiment 1 and experiment 2 took part in this test. The stimuli for this test were
580 synthesized from measurements of the bridge admittance functions of four of the Fylde gui-
581 tars employed in the other tests (Brazilian rosewood, Indian rosewood, sapele, and walnut),
582 and a guitar of a different make and model (Yamaha FG-403MS steel string guitar). Each
583 stimulus had a duration of five seconds. Data collection occurred over the course of two
584 sessions. During the first session participants completed first a practice block of two trials
585 per guitar pair, and then a block of 36 trials per guitar pair. These blocks were randomly
586 ordered. During the second session participants completed an additional block of 36 trials
587 per guitar pair. The presentation intervals were marked by flashing lights on a computer
588 screen, and were separated by 750-ms silent intervals. Participants indicated their responses
589 via key presses mapped to the two response alternatives. Immediate feedback after each
590 trial (a green or red flashing light for correct or incorrect responses respectively) was given
591 during the practice blocks but not during the main blocks (a white flashing light simply
592 acknowledged that a response had been given). The stimuli were generated using a 22,050
593 Hz sampling rate and 16-bit depth. They were sent to a digital-to-analog converter (E-MU
594 0204 USB), and played diotically through Sennheiser HD650 headphones. Participants were
595 tested in a IAC double-walled sound-insulating booth. Because a non-roving, blocked de-
596 sign was used for this experiment, d' values were calculated assuming that participants used

597 an independent observations strategy to perform the ABX task ([Macmillan and Creelman,](#)
598 [2004](#)).

599 C. Results

600 The average d' values obtained by the seven guitarists who took part in this test are
601 shown in Fig. 7. The d' values were modeled as a function of guitar pair, and individual
602 player, using a Bayesian GLM (see supplementary material for details). The d' CIs for each
603 guitar pair are shown in Fig. 8. Performance was very good for the discrimination of the
604 Indian rosewood and Yamaha guitars (posterior d' mode=3.24, CI: 2.74 – 3.78), indicating
605 that players were able to do the test proficiently when the guitars were of a different make
606 and model.

607 Performance in the discrimination of the three guitars that had been tested in the ABX
608 test with real guitars was slightly better than in the previous test, but was nonetheless
609 poor, with d' values around 1 (Braz. rosewood vs sapele d' CI: 0.22 – 1.23; Braz. rosewood
610 vs walnut CI: 0.22 – 1.24; sapele vs walnut d' CI: 0.44 – 1.47). Discrimination performance
611 for the guitar pair with the most divergent modal frequencies was better, but still mediocre,
612 with a d' around 2 (Indian rosewood vs sapele d' CI: 1.54 – 2.51). Overall these results show
613 that although performance in this test with virtual guitars was better than in the playing
614 ABX test, discrimination performance among most of the guitar pairs nominally differing
615 only in their back woods was generally poor. It was still far from perfect even for the guitar
616 pair with the most divergent modal frequencies, but the pattern of the results was generally
617 consistent with the predictions based on earlier threshold tests ([Woodhouse, 2002](#)).

VIII. GENERAL DISCUSSION

The results of this study indicate that the choice of back wood has a minimal effect on the quality of acoustic steel-string guitars, provided that the guitar maker uses each different wood in a suitable way. This conclusion is consistent with earlier expectations from acoustic and psychoacoustic studies of the guitar, and it is supported by converging evidence from our experiments:

1. differences in the body mode properties of the set of six guitars were small, and furthermore the residual differences did not seem to stem mainly from the back wood;
2. players's average ratings for "overall sound" and for playability were similar between the six guitars;
3. performance in a simple ABX discrimination test run under realistic playing conditions was very poor, only slightly better than chance level;
4. performance in an ABX discrimination test of guitar sounds synthesized from the bridge admittance functions of the six guitars was poor for most guitar pairs tested. It was mediocre for the guitar pair with the largest differences in bridge admittance functions; differences that likely reflect residual top plate variability.

A. Rating tests

Experienced guitar players gave, on average, very similar "overall sound" and playability ratings to six guitars with backs and sides made of different woods. Guitarists who rated

637 the guitars twice were also not consistent in their ratings from one session to another. There
638 are several possible explanations for this pattern of results. One possibility is that guitarists
639 did have preferences for different back woods but were somehow unable to express them
640 consistently using the rating scale, perhaps because they were unable to keep track of the
641 ratings they were giving to each guitar. This explanation seems implausible in light of the
642 fact that guitarists did show clear preferences between some instruments in a rating test of
643 the visual appearance of the guitars (described in the supplementary material), which had
644 essentially the same format as the acoustic rating test. The only study that used a rating
645 procedure similar to that employed in the current study for the evaluation of guitar sounds
646 failed to find differences between guitar recordings of three guitars of varying commercial
647 value (Inta, 2007). However, only five participants were tested in that study, and they were
648 asked to listen to several recordings of each guitar, and each time rate it on 34 attributes,
649 which may have substantially increased listener fatigue during the test. Given these issues
650 it is difficult to draw conclusions on the validity of the rating method used in our study from
651 the study of Inta (2007). It should be noted that rating methods similar to the one used in
652 the current study have been often used in studies of consonance perception, in which, for
653 example listeners may be asked to rate the pleasantness of various musical intervals on a
654 scale from -3 to 3 (Bones *et al.*, 2014; Bones and Plack, 2015a,b; McDermott *et al.*, 2010).
655 These studies of consonance perception reliably find differences in the pleasantness ratings
656 given by both musicians and non-musicians to musical intervals according to their degree of
657 consonance.

658 Another potential explanation for the pattern of results obtained in the blinded sound
659 rating test is that back wood preferences are highly subjective: individual players might
660 have clear favorites among woods, but the highly rated woods would be different from
661 player to player. When the ratings are averaged across all players there would be, overall,
662 no ratings differences between guitars. However, this explanation seems implausible in the
663 light of the fact that guitarists that rated the guitars twice were not consistent in their
664 ratings from one session to another, indicating that individual players did not have strong
665 preferences for one or more woods. A parsimonious explanation for both the poor test-
666 retest rating correlations, and the similarity of the average ratings across guitars, is that the
667 perceived differences between the six guitars were so small that players could not rank them
668 consistently either within or across sessions. This explanation is corroborated by the results
669 of the ABX discrimination test, which show that players' ability to discriminate between
670 three of the six guitars was poor, just above chance level.

671 Our finding of poor test-retest consistency of player ratings seems superficially at odds
672 with previous studies on violin players showing that musicians can be self-consistent in their
673 ratings of musical instruments (Saitis *et al.*, 2015). Unlike the guitars of our study, however,
674 the instruments used in these previous studies were of different makes and models, and were
675 intentionally selected to sound different from each other. Given that simply discriminat-
676 ing between the different guitars in the current study was very hard, it is not surprising
677 that players failed to be consistent in their ratings. Additionally, a violinist has access to
678 significantly more information about the instrument than a guitarist does, because of the
679 sensitive way that the “playability” of a bowed string depends on details of the body vi-

680 bration. Different bowing gestures elicit different transient behavior, whereas in a plucked
681 instrument like the guitar the player has very little influence over the form and length of
682 initial transients ([Woodhouse, 2014](#)).

683 In an additional experiment described in the supplementary material (unblinded sound
684 ratings), guitarists did not give credibly different ratings for overall sound or playability to
685 the guitars even when they could see the guitars in full light. This suggests that biases
686 for guitars with prized tropical woods may not be as strong or widespread as surveying
687 the specialized guitar press suggests they are. However, it should be kept in mind that
688 guitarists performed the unblinded rating test only after the ABX test, on which they were
689 given feedback at the end of each session. Because most guitarists were barely able to
690 discriminate the guitars in the ABX test, and were aware of this fact, it is possible that they
691 were more cautious in their ratings in the unblinded rating test, reducing any pre-existing
692 bias for prized tropical woods.

693 **B. Dimensions used by players to evaluate guitars**

694 The results of the EFA on the acoustic ratings of the guitars indicate that a number
695 of perceptual attributes commonly used by guitarists to describe the sound of a guitar are
696 closely related to each other. These attributes revolve around the dimensions of loudness,
697 warmth, and clarity. Our results suggest that these are three of the basic underlying di-
698 mensions used by players to evaluate the sound of a steel-string acoustic guitar, and each of
699 these dimensions is positively related to the “overall sound” rating. The number of factors
700 that can be extracted using an EFA depends on the number and the diversity of descriptors

701 that are used in the rating questionnaire, both of which were limited by time constraints in
702 our experiment. Therefore, we do not claim that loudness, warmth, and clarity are the only
703 dimensions on which the sound of a steel-string acoustic guitar is judged. It should also be
704 kept in mind that a positive association between these dimensions and overall sound rating
705 does not imply a causal relation between them.

706 C. ABX discrimination

707 The results of the ABX tests indicate that discriminating between two guitars nominally
708 differing only for their back wood is very difficult. Although performance was on average
709 slightly above chance level, it was poor. In the test with synthesized guitar sounds perfor-
710 mance was only slightly better. Despite the fact that listening conditions were probably
711 more favorable in this test, because of the absence of any variability in the rendition of the
712 excerpts due to variability in player’s performance and the absence of long delays between
713 excerpts due to the need to physically swap instruments, performance was still poor for most
714 guitar pairs tested, and was only mediocre for the guitar pair with the most divergent body
715 mode frequencies (Indian rosewood vs sapele). The results of the modal analysis strongly
716 point to residual differences in the top plates as the main cause of differences in body mode
717 frequencies between the guitars. Because performance was poor between guitars with min-
718 imal differences in body mode frequencies, and improved only for the guitar pair with the
719 most divergent body mode frequencies, it seems reasonable to attribute this improvement
720 to these differences in modal body frequencies, and hence to residual top-plate differences.
721 Importantly, the ABX test with synthesized guitar sounds explicitly demonstrated excellent

722 discrimination performance between the Indian rosewood guitar and a guitar of a differ-
723 ent make and model. Listeners could easily and reliably perform the ABX task when the
724 differences between guitars were sufficiently large, and not limited to their back wood.

725 A previous study using synthesized guitar sounds established thresholds for detecting
726 a shift of low-frequency body modes. The average performance of the subjects in that
727 test gave a threshold around 3%, while the most acute listeners achieved values around
728 1% (Woodhouse *et al.*, 2012). Thresholds in that study were measured using an adaptive
729 procedure which tracked a d' of 1.6. For comparison, the d' measured in our study for
730 the discrimination of the sapele vs walnut guitars, which have a 3% difference in their low
731 frequency peaks, was around 1. This figure is thus somewhat lower than would be expected
732 on the basis of the results of the previous study. Besides sampling error, this difference may
733 be due to methodological differences between the two studies, such as the use of different
734 stimuli, and the fact that the “natural” modal shifts between the guitars in our study do not
735 precisely match any of the conditions tested by Woodhouse *et al.* (2012), which consisted
736 of either coherent shifts of all low body mode frequencies, or of a shift of only the 200 Hz
737 mode.

738 Some musicians are said to have “golden ears” because of their ability to discriminate
739 subtle differences between sounds that other musicians cannot. Large interindividual dif-
740 ferences in the ability to discriminate changes in basic acoustic attributes such as pitch are
741 common in psychoacoustic studies, although interindividual variability tends to be smaller
742 for trained musicians compared to non-musicians (e.g. Micheyl *et al.*, 2006). One might
743 wonder whether, although on average discrimination performance in the ABX tasks between

744 guitars nominally differing only for their back wood was rather poor, some players were con-
745 sistently good at this task. For the playing ABX test, with only eight trials per condition,
746 the variance of d' is too large to make meaningful statements on individual players' per-
747 formance (Hautus and Lee, 1998; Macmillan and Creelman, 2004). Keeping this caveat in
748 mind, the best performing player, L7, had an average d' across conditions of 2.1 (19/24
749 correct answers), a medium performance level. Individual results for the ABX test with
750 virtual guitars, in which listeners completed 72 trials per condition, are shown in Fig. S7.
751 One listener, L18, tended to perform better than the others across conditions, achieving a
752 relatively high d' of ~ 3 in the Indian rosewood vs sapele condition and in the sapele vs
753 walnut condition. This listener could be said to be discriminating quite well some of the
754 virtual guitar pairs nominally differing only for their back wood. However, given that the
755 results of the modal analysis strongly suggest that modal differences did not stem mainly
756 from the back wood, it is likely that his ability to discriminate between these guitars was
757 based on modal cues caused by residual differences in the top plates, rather than by the
758 different back plates.

759 **D. Generalizability of results**

760 There are many factors that could conceivably limit the generalizability of our results,
761 including the limited number of wood species that was tested in our study, the within-species
762 variability of mechanical wood properties, the various possible choices in the guitar design
763 including its shape, size, and bracing patterns, and the testing conditions. Each of these
764 factors will be discussed below.

765 Only a limited number of wood species could be tested in our study. However, the
766 woods selected included some of the most popular woods used for guitar backs, such as
767 Indian rosewood and mahogany, as well as Brazilian rosewood, which is often considered
768 the “gold standard” among back woods. These woods were compared to some less well
769 regarded wood choices such as sapele and walnut. The lack of significant differences in
770 “overall sound” ratings between the woods tested in our study may not extend to other
771 untested wood species, but this does not invalidate the main conclusion of our study that,
772 under blinded conditions, highly prized and expensive woods such as Brazilian rosewood are
773 not necessarily preferred by guitar players to lesser-known, much less expensive woods. Our
774 study investigated only solid woods, and therefore does not address the question of whether
775 other materials like laminates or carbon fiber composites, already introduced in the market
776 by several guitar companies, can substitute solid woods without loss of sound quality. This
777 is an important question that we hope will be addressed by future studies.

778 Wood is a biological tissue, and as such it inevitably shows some variability in mechanical
779 properties within the same species. Furthermore, as illustrated in Fig. 2, the properties of
780 the final back plate can be sensitively influenced by how the board is cut from the log.
781 However, the wood for each guitar used in our study was carefully selected by the luthier
782 to be typical of each species according to his decades-long experience in guitar making. For
783 this reason, we believe that the acoustic characteristics of the guitars were typical of guitars
784 with backs made of those woods. Residual variability of the top plate woods (even though
785 they were all cut from the same flitch), and variability due to small details of fabrication
786 ([French, 2008](#)), could have affected the results of individual comparisons between our guitars

787 to some extent. However, it is very unlikely that variability due to all of these factors could
788 have conspired to make all six guitars have very similar ratings for overall sound quality
789 and playability. This argument is supported by the fact that the playability and overall
790 sound ratings variance estimates of the superpopulation of guitars nominally differing only
791 for their back wood was low, indicating that back wood differences have only a minor impact
792 on overall sound and playability ratings.

793 The design of a steel-string acoustic guitar involves many choices, including its shape,
794 size, and bracing pattern. Only a single design was tested in our study, so it is not guaranteed
795 that our results would generalize to guitars built with different designs. It should be pointed
796 out, however, that the design chosen for our guitars is one of the most commonly used for
797 steel-string acoustic guitars, so our results should generalize to a large number of guitars
798 that are built with similar designs. Furthermore, the results shown here have confirmed
799 predictions from earlier acoustical modelling: the influence of the back plate on the low-
800 frequency modes is limited and well-understood ([Christensen and Vistisen, 1980](#); [Fletcher
801 and Rossing, 1998](#); [Richardson, 1994, 2002](#)), and it should be possible for the guitar maker
802 to compensate for material variations to a very large extent.

803 The time that each guitarist could spend playing and listening to each guitar in our exper-
804 iment was limited, in the order of minutes. It is possible that if guitarists could have played
805 the guitars for longer periods of time, in the order of hours, days, or perhaps years, their
806 ability to discriminate between the guitars, as well as the consistency of their ratings across
807 sessions, could have been higher. It is well known that the ability to discriminate sounds
808 on the basis of simple perceptual attributes such as pitch or loudness ([Carcagno and Plack,](#)

809 2011) can improve dramatically with practice, a phenomenon known as auditory perceptual
810 learning. This phenomenon, however, is much less pronounced for musicians (Michey *et al.*,
811 2006), who are already experienced listeners owing to years of musical practice. Despite
812 this, we cannot exclude the possibility that longer practice with the instruments could have
813 improved the results of the discrimination test, and possibly led to a different ranking of
814 the guitars in terms of their overall sound and playability. However, the very idea that even
815 experienced guitar players may need an extended period of perceptual learning to appreciate
816 differences between back woods would indicate that such differences are very small. Large
817 differences in the sound of two guitars should be immediately apparent without training,
818 especially for experienced guitar players. The constraints on the time each guitarist could
819 play the guitars were imposed mainly for practical reasons (longer or additional testing ses-
820 sions would have been required otherwise). However, these time constraints are also relevant
821 because they mimic to a certain extent what would typically happen in a guitar shop, where
822 a player may spend minutes (rather than hours or days) playing and evaluating a small
823 number of guitars before making a decision on which one to buy.

824 E. Conclusions

825 The results of our study indicate that steel-string acoustic guitars with backs and sides
826 built using traditionally prized, expensive, and rare woods are not rated substantially higher
827 by guitarists than guitars with backs and sides built using cheaper and more readily available
828 woods. The poor ability of guitarists to discriminate under blinded conditions between

829 guitars with backs and sides made of different woods suggest that back wood has only a
830 marginal impact on the sound of an acoustic guitar.

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837 per is available from https://osf.io/f4pqa/?view_only=885abfa348324c5cbe8bf409a543601a
838 [This is a temporary URL, we will provide a DOI once the manuscript is accepted].

839 ¹See supplementary material at [URL will be inserted by AIP] for additional methods details, additional
840 figures, and additional results.

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958 **TABLES**

	F_1	Q_1	F_2	Q_2	F_3	Q_3
Back wood	(Hz)		(Hz)		(Hz)	
Brazilian rosewood	97	34	177	18	336	36
Indian rosewood	101	38	188	26	368	58
Maple	100	35	187	25	363	53
Mahogany	99	33	184	25	351	35
Sapele	96	39	175	17	335	44
Walnut	98	42	182	28	347	24

TABLE I. Measured modal frequencies and Q factors of low-frequency modes of the set of guitars.

TABLE II. List of questions used in the sound rating tests.

Q1	How do you like the overall sound of the guitar?
Q2	How do you like the playability of the guitar?
Q3	How bright is the sound of the guitar?
Q4	How clear is the sound of the guitar?
Q5	How warm is the sound of the guitar?
Q6	How mellow is the sound of the guitar?
Q7	How balanced is the sound of the guitar?
Q8	How defined is the sound of the guitar?
Q9	How strong is the tone separation of the guitar?
Q10	How complex is the sound of the guitar?
Q11	How rich is the sound of the guitar?
Q12	How strong is the projection of the guitar?
Q13	How strong is the sustain of the guitar?
Q14	How wide is the headroom of the guitar?
Q15	How loud is the guitar?
Q16	How big is the sound of the guitar?

959 **FIGURE LEGENDS**

960 **FIG. 1.** (Color online) (A) Bridge admittance of the six experimental guitars. For com-
 961 parison the bridge admittance of a different steel-string acoustic guitar (Yamaha FG-403MS)
 962 that was not part of the experimental set is also plotted. (B) Bridge admittances used for
 963 the synthesis-based listening tests described in Section VII, calculated from the measured
 964 admittance of a reference guitar, but modifying the low-frequency modal parameters as
 965 described in the text.

966 **FIG. 2.** (Color online) Measured (A) density and (B) stiffnesses of the tested wood
 967 samples. For each wood, two black symbols correspond to the two halves of one set, and
 968 two red symbols to the two halves of the second set. For the stiffnesses, stars denote D_1 ,
 969 circles D_3 and + symbols D_4 .

970 **FIG. 3.** (Color online) Average “overall sound”, and playability ratings obtained for
 971 each guitar in the blinded sound rating test. Error bars denote ± 1 standard error of the
 972 mean (s.e.m.).

973 **FIG. 4.** (Color online) Bayesian posterior mode estimates (filled symbols) and 95% CIs
 974 (horizontal segments) for the rating differences in overall sound and playability between each
 975 guitar pair in the blinded sound rating test. The gray dotted lines mark a distance of ± 0.2
 976 points on the rating scale.

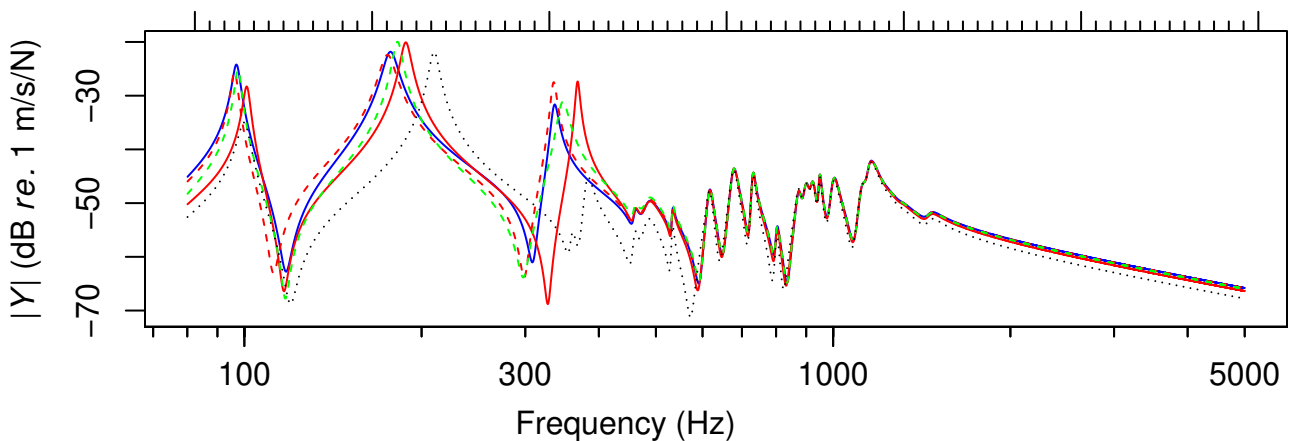
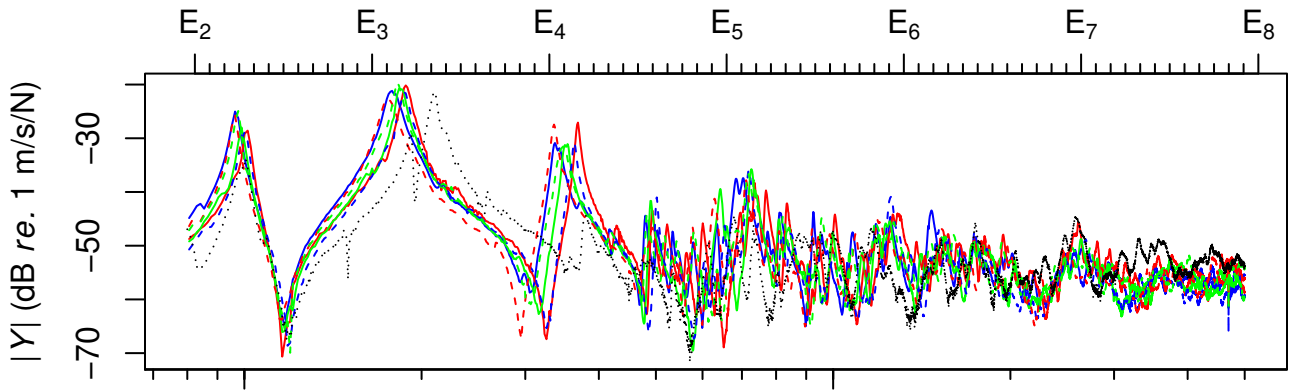
977 **FIG. 5.** (Color online) Average d' values obtained for each guitar pair in the ABX test,
 978 as a function of player professional status. Error bars denote ± 1 s.e.m.

979 **FIG. 6.** (Color online) Bayesian posterior mode estimates (filled symbols) and 95% CIs
980 (horizontal segments) of d' for each guitar pair in the ABX test, as a function of player
981 professional status.

982 **FIG. 7.** (Color online) Average d' values obtained for each guitar pair in the ABX test
983 with virtual guitars. Error bars denote ± 1 s.e.m.

984 **FIG. 8.** Bayesian posterior mode estimates (filled symbols) and 95% CIs (horizontal
985 segments) of d' for each guitar pair in the ABX test with virtual guitars.

— Indian Rsw. - - - Sapele
— Mahogany - - - Walnut

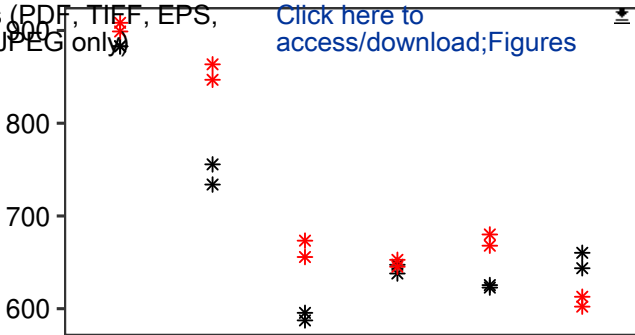


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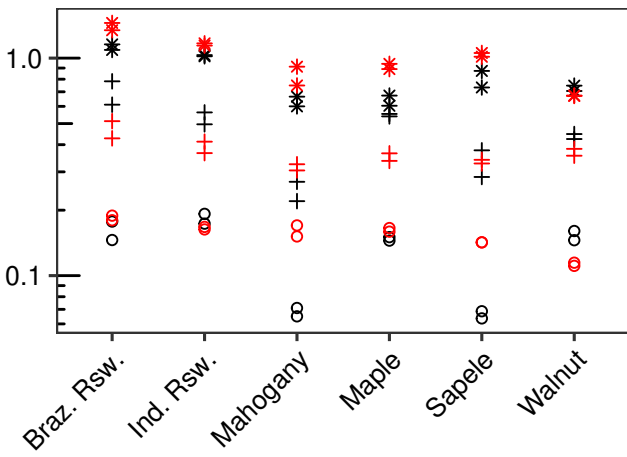


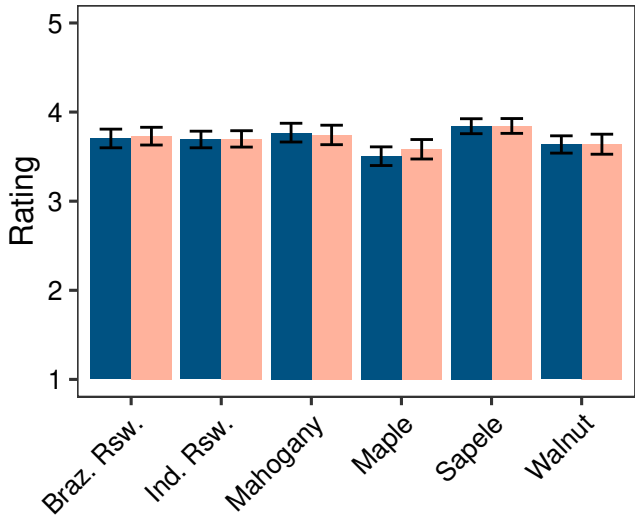
Density (kg/m^3)



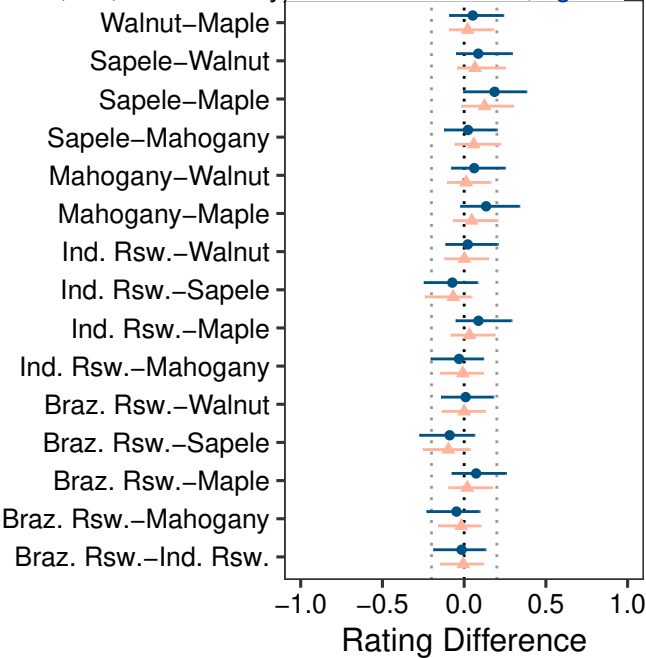
B

D value (GPa)



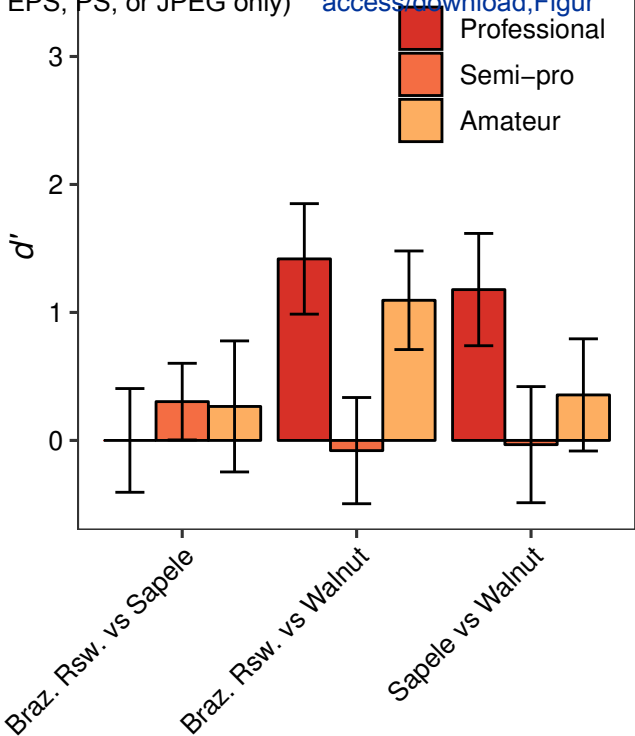


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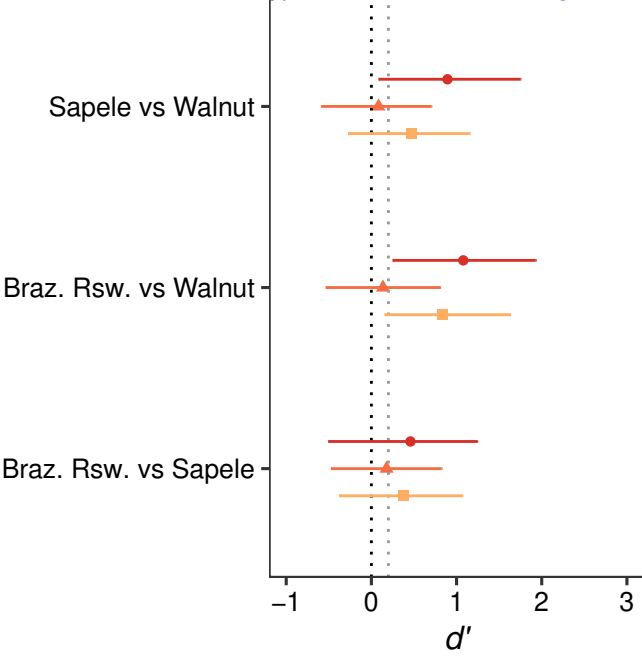


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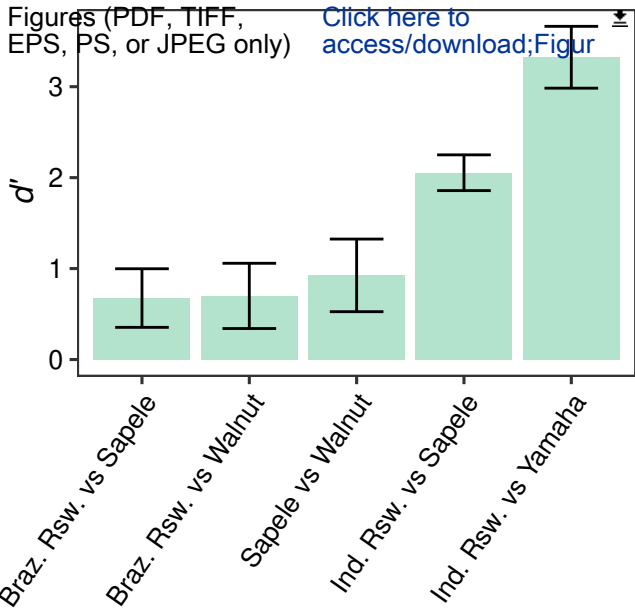


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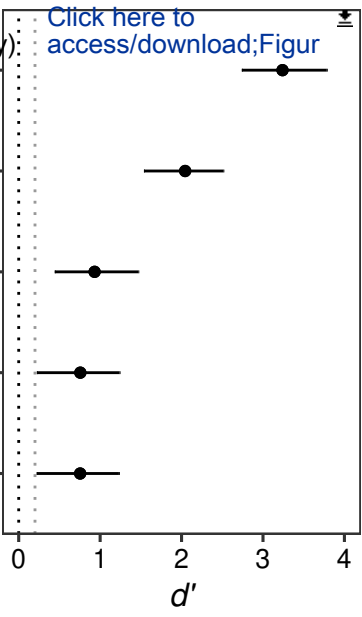
Ind. Rsw. vs Yamaha

Ind. Rsw. vs Sapele

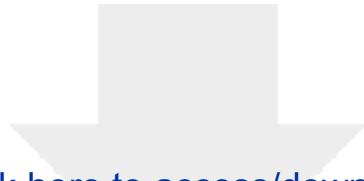
Sapele vs Walnut

Braz. Rsw. vs Walnut

Braz. Rsw. vs Sapele

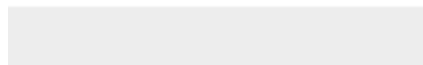


0 1 2 3 4
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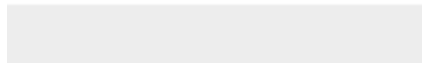
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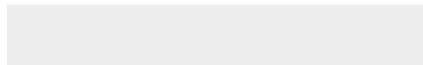
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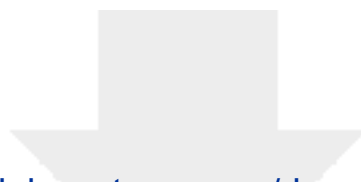




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