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Citation: The Journal of the Acoustical Society of America **146**, 2608 (2019); doi: 10.1121/1.5129395
View online: https://doi.org/10.1121/1.5129395
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Perceptual evaluation of bracewood and soundboard wood variations on the preference of a steel-string acoustic guitar

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(Received 24 May 2019; revised 27 September 2019; accepted 27 September 2019; published online 23 October 2019)

The wood of the spruce tree (*Picea spp.*) has been valued for centuries as an ideal soundboard for stringed instruments due to its material acoustic properties. There is large variability in these properties between individual trees of the same species and even within an individual log. It stands to reason that this variability would produce audible differences in the sound quality of otherwise identical musical instruments. Furthermore, there may be a suite of physical characteristics of the soundboard that would result in optimal sound quality for a given design. Nine steel-string guitars of the same model were produced. The guitars varied only in two parameters: the density and Young's modulus of the soundboard and bracewood. This variability was representative of the range of wood currently produced by Pacific Rim Tonewoods. A short music sequence was used for a pairwise preference evaluation in a listening test. The results suggested that, for this particular model (the Taylor 814ce Grand Auditorium), the low density and Young's modulus of the soundboard and bracewood had a positive impact on the sound quality. More generally, these results underscore the importance of integrating a given design with the physical characteristics of the component wood. © *2019 Acoustical Society of America*. https://doi.org/10.1121/1.5129395

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I. INTRODUCTION

The vibrating system of a guitar consists of multiple coupled resonators: the strings, guitar body, and enclosed air volume. Many factors influence the resulting sound, including the design characteristics of these coupled resonators, such as the soundboard bracing scheme, the size and shape of the resonant chamber, and other constructive details. However, the material properties of the wood itself, particularly the soundboard wood, can significantly influence the quality of the perceived sound (Ziegenhals, 2001). The aim of this paper is to investigate the influence of two material properties, density and Young's modulus, on the tonal quality of the resulting guitar using the example of a specific steel-string acoustic guitar.

A. Tonewood parameters

In traditional music instrument making, the selection of the resonance wood is of crucial importance (Oribe, 1985). The wood has to satisfy basic requirements, e.g., a high surface hardness, stability to variations in temperature and humidity, and long-term resistance to deformations under the mechanical loading induced by string tension. Commonly used species for guitar tops satisfying these criteria are spruce (*Picea spp.*) and cedar (*Thuja spp.*). However, the material properties of timber are highly variable, even within species, and even within the wood of a single log. Instrument makers therefore select tonewoods very carefully (Bourgeois, 1994). From experience, various criteria have been established for this purpose. Usually, a selection is made initially based on aesthetic considerations. For guitar soundboards, wood is selected based on the uniformity and average width of the annual rings, ratio of latewood, and absence of irregularities, e.g., spiral grain (Brandstätter, 2016). Additionally, the selection is often complemented by bending and tapping tests, whereby the luthier may acquire an impression of the resonance characteristics by interpreting the loudness, pitch, and timbre of the tap tone and the weight and stiffness of the material.

With current technology, one can objectively and accurately measure the relevant dynamic mechanical properties using acoustic techniques. According to acoustical theory, the relevant properties are primarily the density ρ, moduli of elasticity (Young's and shear moduli), and damping (Wegst, 2006). For wood Young's modulus varies in the directions perpendicular (radial) and parallel (longitudinal) to the grain. The stiffer longitudinal direction helps to withstand the tension of the strings. For a given guitar design, Young's modulus is also (together with the mass) the determinant for the modal behavior and acoustic radiation, especially for the lowest resonance frequency (first mode), and will therefore be varied in this study. The radial Young's modulus influences the frequencies of higher modes (Baltrusch, 2000). This study focuses on the longitudinal Young's modulus and density only. The square root of the ratio of the longitudinal Young's modulus and density defines the speed c of longitudinal sound waves in a material,

$$c = \sqrt{\frac{E_L}{\rho}}. \quad (1)$$

Therefore, measuring the speed of sound is an efficient way to determine material characteristics. Incidentally, c is also

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 0001-4966/2019/146(4)/2608/11/$30.00 © 2019 Acoustical Society of America

proportional to the natural frequencies of a plate. The lower c is, the lower the natural frequencies. However, the modal behavior of a guitar is also dependent on the design of the guitar. Some luthiers argue that good instruments can be made relatively independent of the wood properties, e.g., by varying the geometrical properties of the soundboard and bracing according to acoustical rather than dimensional tolerances (Gore, 2011). This procedure can lead to good results but is time-intensive and therefore costly. Additionally, there is some disagreement regarding which acoustical properties are perceptually relevant. Therefore, this study seeks to investigate whether the selection of top wood based on specific material parameters can help produce an appreciable and reproducible impact on the perceived sonic quality of the resulting instrument.

For c, high values are displayed as positive (Richardson, 2002; Ziegenhals, 2001). This suggests that soundboards should be light and stiff, which is also a common demand of luthiers (Brandstätter, 2016; Dunn, 2013). Some publications discuss the quality of resonance wood by calculating c or other physical values, e.g., the damping characteristics (Spycher *et al.*, 2008; Wegst, 2006). However, the absolute and relative importance of such values needs to be proven in perceptual studies.

B. Psychoacoustics of the guitar

Although the construction of guitars has a long history, scientific studies from a perceptual point of view have been published rather recently.

Different methodologies exist to evaluate musical instruments perceptually. To simulate a real-life context, e.g., choosing an instrument in a store, multiple instruments can be compared in a playing test. The player can be asked to judge different criteria related to the quality of the sound, but other parameters, such as playability, can also be examined (Fritz and Dubois, 2015). Playing tests may be adversely biased by nonmusical attributes, such as the appearance of the instrument (Ziegenhals, 2010). Such biases are typically addressed by limiting the vision of the participant, e.g., by using welder's googles in a dimly lit room (Carcagno *et al.*, 2018) or dark sunglasses (Saitis *et al.*, 2012).

An alternative to playing tests is to replay recorded music samples in a blind listening test. In this case, the influence of the player and the selected musical sequence is specifically included in the recording. The focus of such an experiment is shifted to purely acoustical features. The interaction with the instrument, e.g., the playability, cannot be investigated in a listening-only test.

In both cases, playing and listening tests, the participants can be interviewed or asked to verbalize their impression of an instrument (followed by a linguistic analysis) and/or rank multiple instruments by order of preference (Saitis, 2013). More often, questionnaires are used to rate different perceptual criteria using a grading scale, e.g., brightness, dynamics, clarity, or sustain (Fritz and Dubois, 2015). However, such predefined criteria might (unintentionally) suggest which parameters are presumably important regarding the overall quality of the instrument. Therefore, global judgments should be assessed before or separate from other perceptual properties. In the current study, the overall preference is of major interest. Therefore, to avoid interference with predefined concepts, only preference comparisons are carried out.

A previous study on classical nylon-stringed guitars reported that varying the soundboard wood significantly changed the perceptual impression. For example, it was found that the longitudinal stiffness and mass of the soundboards correlated with subjective quality ratings in both a playing and a listening test Ziegenhals (2001). A lower-density top wood was correlated with a better perceptual evaluation of the instruments. However, in contrast to the traditional recommendation, a low longitudinal $E_L < 12\,\text{GPa}$ and low values for the speed of sound c were found to be beneficial if woods from different species were compared (Baltrusch, 2000). It is an open question whether similar trends can be found within wood species when varying only the material parameters. It also remains to be examined whether the determined relations are valid for a steel-string acoustic guitar.

The perceptual effect of the back wood has been investigated recently for classical guitars (Ziegenhals, 2015) and steel-string guitars (Carcagno *et al.*, 2018). In both cases, various wood species (varying in multiple physical attributes) were included, and among other experiments, playing tests were carried out. Either a marginal influence or no influence of the back wood species on the perceived overall sound rating was reported.

Other research has focused on the perceptual thresholds for changes in the modal properties of the guitar body. Listening tests with synthesized sounds were performed (Woodhouse *et al.*, 2012) using a similar psychoacoustical methodology that was previously applied for evaluating violin sounds (Fritz *et al.*, 2007). It was found that the best listeners were able to perceive even slight shifts of the body frequencies by approximately 1%. Just noticeable differences in the body mode damping were found to be higher in the range of 20%. These findings suggest that variations between actual instruments that exceed these differential thresholds should be audible. However, preference was not studied explicitly, so no conclusions could be drawn regarding the relative quality of these perceptual differences.

Previous studies with classical nylon-stringed guitars tried to correlate perceptual ratings, e.g., the overall quality, with measured parameters derived from the modal behavior or sound radiation (Czajkowska, 2014; Ziegenhals, 2010). However, contradicting features were considered to be important, e.g., levels and audio spectrum flatness in diverse frequency bands or the levels and frequency locations of different single modes. Additionally, only correlation or regression results were reported, and the underlying perceptual data were not reported. A critical review of similar studies of the perceptual evaluation of many kinds of musical instruments, with a focus on violins, can be found in Fritz and Dubois (2015).

This article focuses on the perceptual preference ranking of a group of guitars, including a detailed statistical analysis. The influence of the basic physical properties of the top wood (ρ and E_L) is discussed. However, the correlation of the perceptual data with the objective acoustical parameters of the finished instruments is beyond the scope of this article and will be addressed in future studies.

II. MEASUREMENT AND SELECTION OF THE TONEWOOD

The production of tonewood is a highly specialized endeavor that involves carefully selecting a log, milling the log into rounds that are the length of a guitar soundboard, splitting the wood along the longitudinal grain into quarter rounds, and sawing the quarter rounds into precise quarter sawn billets of standard dimensions. Milling wood in this fashion maximizes the radial and longitudinal Young's modulus (E_R and E_L, respectively) and the bending strength for each top. The degree of deviation from the vertical "end grain" (the growth rings along the tangential axis) is particularly critical, with deviations greater than 3° resulting in quantifiable reductions in E_R and deviations of 10° resulting in a loss of 40% to 50% (Schleske, 1990). Careful milling of the billet ensures that the material variability present in the finished soundboard reflects the intrinsic properties of the wood and not variations in the milling technique (Ross, 2010). These billets are then re-sawn into individual bookmatched soundboard tops approximately 4 mm in thickness, with two "sister sets" of tops produced from each billet. Each of these tops is then subjected to rigorous inspections, rejecting tops with defects such as pitch pockets, knots, and reaction wood. The tops that pass these rigorous inspections are then graded by aesthetic means, with criteria specified by the client. Pacific Rim Tonewoods, Inc. (PRT) of Concrete, WA, is a specialty sawmill entirely dedicated to the production of guitar tonewood. PRT produces 300 000 guitar tops per annum and over one million linear feet of bracewood, with 80% being the wood of a single species, Sitka spruce (*Picea sitchensis*).

Until this study, no attempt has been made by a specialty sawmill to grade wood by acoustic criteria. However, basic material properties can be determined quickly and reliably using nondestructive grading. To this end, the BING software system by Pico Technology (St Neots, United Kingdom) is used to analyze standardized rectangular billets of test wood in the current study. This system uses the natural resonance frequencies of the test pieces to derive the elastic constants and damping (Brancheriau and Bailleres, 2002). The pieces were suspended on elastic supports at their natural nodes, 22.4% of their overall length, and the standard impact of dropping a steel ball (9 g, 13 mm in diameter) on the pieces was used to induce a transverse wave on one end of the board, with a microphone on the other end. The microphone was an omnidirectional Rode M3, and the analog signal was converted to digital with a Picoscope 3224 (Pico Technology). The recordings were performed on a custom steel frame that integrated the dropped steel ball at a standard distance of 2.5 cm above the board. The frame was supported on vibration isolating damping material (Isolate-It, Sorbothane), and the workspace was surrounded by 5 cm acoustic foam.

There is a substantial body of literature that relates the geometry and density of a test beam, its resultant resonance frequencies, and the subsequent derivation of the dynamic elastic constants. Applied correctly, these techniques can derive the longitudinal Young's modulus (E_L) and shear modulus in the longitudinal-radial plane. In addition, the dynamic nature of these tests allows for measurements of the logarithmic decrement at the resultant resonance frequencies and a derivation of the internal friction.

Tests were performed on boards that measured 545 mm (longitudinal) × 220 mm (radial) × 21 mm (tangential). The Timoschenko model with the Bordonne solution (a subset of the Euler–Bernoulli formula) was applied to calculate E_L and the shear modulus. The details of the theory and a discussion of the possible error relative to other measurement techniques can be found in Brancheriau and Bailleres (2002). The relative standard deviation for E_L was calculated for our dataset by serially recording data from ten boards, with ten replicate measurements per board. The mean relative standard deviation was low, less than 0.1%. This result was in line with a similar low standard deviation of E_L from a previous study on xylophone bars using the same technique (Brancheriau *et al.*, 2006).

Young's modulus across the grain (E_R) was determined by a dedicated ultrasound meter (Lucchi meter, Cremona Tools, Cremona, Italy). The speed of sound in the radial direction was measured, and the corresponding Young's modulus was calculated using the adaptation of Eq. (1). To minimize the impact of E_R as a variable, the boards were initially screened for deviations of the end grain from the vertical, with the degree of variability ranging from 0° to 6° and the mean deviation not exceeding 3° for the billets used in this study. Additionally, the billets were selected to reflect a mean radial velocity of 1991 m/s, with a relative standard deviation of 2.5%.

In addition to the soundboard billets above, smaller bracewood billets of standardized dimensions, particular to the manufacturer's needs, were produced. For this study, bracewood billets of 474 mm (longitudinal) × 60 mm (radial) × 19 mm (tangential) were selected from a random sample of Sitka logs representing the standard billets supplied to the Taylor Guitar Co. (El Cajon, CA). Approximately 800 bracewood billets (Fig. 1) and nearly 500 soundboard billets (Fig. 2) of Sitka spruce were dried in a dehumidifying kiln to 8%, according to standard PRT practice. The billets were further conditioned in a climate chamber at 45% relative humidity for a minimum of 3 months and separated by wooden spacers to ensure even drying. Figures 1 and 2 thus comprise a representative sample of the natural variability of Sitka spruce, as currently supplied to the acoustic guitar industry. Figures 1 and 2 illustrate the well-established correlation between density and longitudinal Young's modulus for both the bracewood and soundboard billet datasets. The density of the dataset ranges from 352 kg/m^3 to 540 kg/m^3, and the mean is 428 kg/m^3 (standard deviation: 42 kg/m^3). The mean E_L is 14 222 MPa (standard deviation: 1817 MPa). Recall that the formula for the longitudinal velocity is simply the square root of E_L/ρ; thus, the least squares regression line through these datasets, over this range of ρ, represents

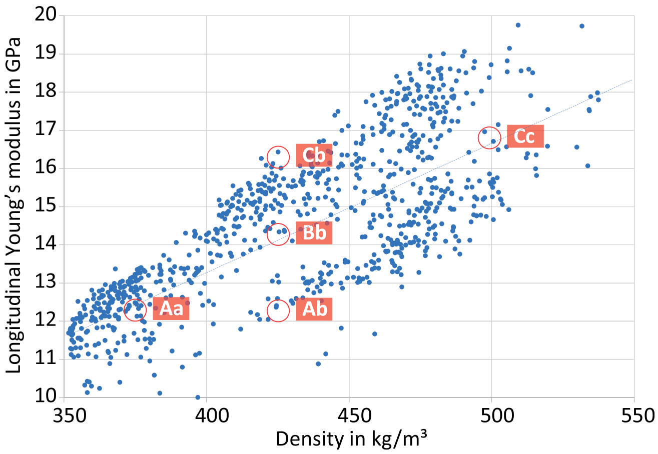

FIG. 1. (Color online) Longitudinal Young's modulus and density of 800 pieces of bracewood. The circles mark the selected positions used for varying the bracewood in the first group of guitars. In the second group, only bracewood from position Bb was used for all guitars.

nearly an isoline for the velocity and will be treated as such for the remainder of the discussion.

The relationship between E_L and ρ exhibits a R^2 of 0.61 in these datasets. The remainder of the variability between specimens, nearly 40%, is explained by other factors intrinsic to the wood, chiefly the cellulose microfibril angle of the S2 layer of the tracheid cell wall. The microfibril angle and wood density exhibit variability both within a log and between logs, and both factors are thought to be influenced by both genetic and environmental effects (Ross, 2010). This wide variability in the physical characteristics and the effects on the tonal quality of the finished instrument are important in the present study.

Figure 1 shows the dataset for the 800 bracewood billets, along with the position of the selected samples in this group. All of the bracewood billets that fall along the least squares regression line feature a similar median velocity (approximately 5770 m/s) but different densities and stiffnesses: low (Aa), median (Bb), and high (Cc). The vertical axis (Ab, Bb, and Cb) represents the bracewood billets that vary in velocity (and E_L) but have the same median density (425 kg/m^3 in this dataset).

Figure 2 shows the material properties of the soundboard wood. Again, all of the samples along the regression line represent similar median velocities but varying densities and E_L: low (Aa′), median (Bb′), and high (Cc′). The vertical axis (Ab′, Bb′, and Cb′) represents the soundboard wood samples that vary in velocity (and E_L) but have similar densities.

The Taylor Guitar Co. is currently the largest manufacturer of quality guitars in the United States and has gained a reputation for outstanding quality control and build consistency (French, 2008). The "flagship" model, the 814ce Grand Auditorium (2017), was selected for this study. The 814 is one of Taylor's most popular models and can be considered an archetype of the Taylor brand. All Taylor models prior to a significant redesign in 2018 have incorporated the traditional "X-braced" scheme. We decided to use this design for this study to allow for perceptual comparisons with a known and well-established sonic profile.

Considerable effort was made so that the only practical difference between the guitars was the acoustic characteristics of the top (soundboard and bracewood). The guitars were built from the same density class of seasoned and premeasured wood (East Indian rosewood, mahogany, ebony, and granadillo) for the backs/sides, neck, bridge, fret board, and pin block. The guitars were built sequentially by the same team of luthiers, with a factory setup by Taylor's lead technician. After conditioning the wood, blanks were cut into shape using lasers in a climate-controlled room and sanded to an even thickness. Computer-controlled equipment, Computerized Numerical Control, milling machines, and industrial robots were used to ensure high control over the quality of the build. Nonetheless, some parts are handmade, mainly for decorative aspects (French, 2008).

Two groups of five guitars each were designed to test the effect of varying both E_L and density on the sound quality. In the first group, both the soundboard wood and the bracewood were varied. In this group, the bracewood and soundboards were always paired such that both exhibited similar material properties. The resulting five guitars were labeled according to Fig. 1, e.g., guitar Aa was built using bracewood Aa and soundboard wood Aa′ or guitar Ab used bracewood Ab and soundboard wood Ab′. Table I presents an overview of the resulting labeling of the guitars.

In the second group, the soundboard was varied, but the bracewood exhibited constant (within a couple of percentage points) mean values of the density and E_L (Bb). The soundboard wood, however, varied across the range. The resulting five guitars were labeled according to Fig. 2, e.g., guitar Aa′ was built using soundboard wood Aa′ but bracewood Bb or guitar Ab′ used soundboard wood Ab′ but also bracewood Bb. The wood used for the soundboards in the second group was actually cut from the same block as those in the first group, making them sister sets. Guitar Bb′ was the same as guitar Bb, which was designed to fall on the median for both groups.

To compare the resulting instruments in a blind listening test, a prototypical music sequence was recorded. The

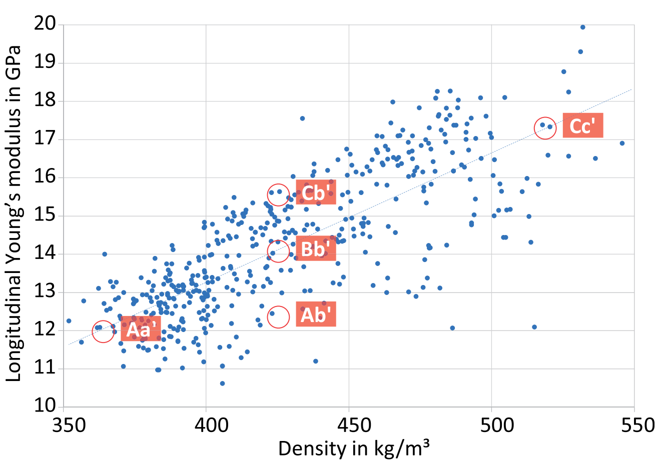

FIG. 2. (Color online) Longitudinal Young's modulus and density of 480 pieces of soundboard wood. The circles mark the selected positions used for building the soundboards in both groups of guitars.

TABLE I. Physical characteristics of the top and bracewood of each guitar. Note that Bb and Bb′ are the same guitar and thus a common link between groups 1 and 2.

		Soundboard		Bracewood	
Guitar		Stiffn.	Density	Stiffn.	Density
Group 1	**Aa**	Low	Low	Low	Low
	Ab	Low	Med	Low	Med
Varying sound-	**Bb**	Med	Med	Med	Med
boards and	**Cb**	High	Med	High	Med
bracewood	**Cc**	High	High	High	High
Group 2	**Aa′**	Low	Low	Med	Med
	Ab′	Low	Med		
Varying sound-	**Bb′**	Med	Med		
boards and con-	**Cb′**	High	Med		
stant bracewood	**Cc′**	High	High		

selection and recording procedures are described in Sec. III. Afterwards, the design and setup of the perceptual experiment are described.

III. SELECTION OF THE STIMULUS

Musical sequences used in listening tests must be carefully selected, and evidence-based guidelines exist to assist in this selection, a selection that is essentially a compromise between somewhat competing objectives (ITU-R BS.1116-3, 2015). A musical sequence should be simple to allow for accurate repetition by players and should be short in duration (5–20 s) to avoid fatigue. However, the selected sequence should also be representative of the full range of the instrument. Additionally, music with rousing or frightening content should be avoided to prevent a distraction from the rather difficult task of detecting sometimes subtle differences in tone.

The selection was made in cooperation with the guitarists who were involved in the subsequent recording. After considering all the above criteria, one strumming sequence was chosen as being most representative of the tone and most illustrative of the differences between the guitars. The strumming sequence consisted of a simple stroking pattern with five chords: C, $D^{add9/11}$, e^{add9}, $D^{add9/11}$, and C. The tempo was set to a moderate 70 bpm. This resulted in a total length of approximately 10 s. The recording was extended for another 6 s to capture the sustain of the final stroke. The sheet music is shown in Fig. 3.

IV. RECORDING OF THE STIMULI

Prior to recording, a senior technician from the Taylor Guitar Company evaluated the instruments on site to ensure that the instruments were "set up" to the ideal factory specifications. The instruments were strung at the same time with Elixir Light Gauge Nanoweb (0.12–0.53) strings and played for 10–15 min prior to the recording. The selected music sequence was recorded with all the guitars.

The recording and playback for the listening tests were performed with the goal of replicating the live performance as accurately as possible. To minimize the influence of the recording method on the sound of the guitar as much as possible, we decided to record the sound with a single omnidirectional microphone placed 2 m in front of the sound hole of the guitar. Additionally, the influence of the room was excluded from the recording using an anechoic chamber. This anechoic recording was later reproduced using a mono loudspeaker in a normal studio room that the listeners used for the listening tests. As a result, the reverberation of the room was included in the reproduction scenario. The loudspeaker thus replaced the real instrument so that pairwise comparisons could be conducted in a listening test in a fashion that allows for a "live" experience. A neutral high-quality microphone, in this case a G.R.A.S. 40HL, was used for the recording. This microphone is intended for free-field measurements and provides a flat frequency response (±3 dB from 6 Hz to 20 kHz) and a wide dynamic range [6.5 dB(A) to 110 dB]. A HEAD acoustics SQuadriga II front end was applied together with the HEAD Artemis software for recording at a 48 kHz sample rate. The recording position was sufficiently far from the guitar to homogeneously integrate the sound radiated from different instrument parts. If this sound is reproduced by a single speaker, the directivity pattern of the speaker will replace the directivity of the instrument. This technique was selected over other reproduction methods, such as using speaker arrays or stereophonic techniques, after a pilot test with five participants compared this technique with a live performance. The participants reported that only very small spatial differences were audible. No changes in the spectral or temporal characteristics could be detected by the participants, who were all academic acousticians. It was assumed that the modifications of the wood in this study mainly influence spectral and temporal cues. Therefore, the recording and reproduction method described above was chosen for further paired comparison experiments. Another option would have been to use

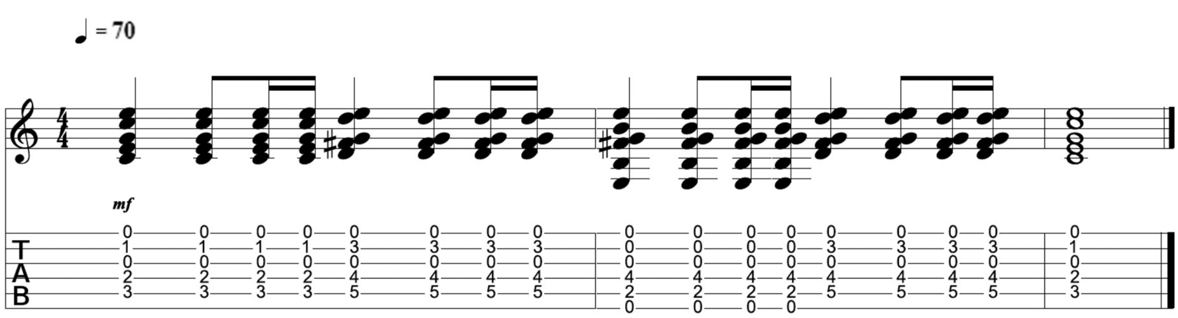

FIG. 3. Sheet music with tabs for the strumming sequence: C, $D^{add9/11}$, e^{add9}, $D^{add9/11}$, and C.

binaural recordings. The main argument for such head-related recordings is the aim of accurately reproducing the spatial sound image, including room reflections. However, there are many possible sources of error (e.g., non-individual recordings or a difficult headphone calibration) that might change the spatial image and tone color.

A professional guitarist was invited from the Academy of Music "Carl Maria von Weber" in Dresden. It is self-evident that playing techniques and individual style significantly influence the sound of a guitar. However, it was assumed that some characteristics of an instrument can be heard independent of individual style. The guitarist was instructed to perform the sequences naturally using a plectrum and to maintain a constant playing style. To be able to switch seamlessly between instruments in a pairwise comparison, it was necessary to keep the tempo between recordings synchronous. Therefore, a metronome was used to generate a click track, which was played via in-ear headphones in one ear of the guitarist. The level was reduced to a minimum so that the clicks were not audible in the recording. The absolute position of the guitars relative to the microphone was kept constant to avoid changes in the overall recording level. Therefore, the guitarist remained seated throughout the recording to ensure a constant relationship between the face of the soundboard and the microphone. A photograph of the recording setup is shown in Fig. 4.

The strumming sequence was recorded twice for each instrument. As expected, some variation occurred over time within a single recording and between repeated recordings of the same instrument. The variation in the level vs time is illustrated in Fig. 5 for the strumming sequence that was played twice on guitar Cc. There are apparent deviations of a few decibels for individual strikes. However, the deviation of the overall level was only 0.7 dB in this example. The mean difference between the overall levels of the repeated recordings for all guitars was 1.2 dB. If the mean levels are compared for the different instruments, the standard deviation is approximately 0.7 dB, which is similar to the variation between the repeated recordings. We decided not to adjust the overall level of the recordings to compensate for variations in the playing style or the variation between the instruments. However, repeated recordings can be included in the following listening experiment to test if the variation in the sound between repeated recordings of the same instrument is perceptually distinguishable from the variation between different instruments. All recordings can be downloaded together at https://doi.org/10.17605/OSF.IO/QK5VE.

FIG. 4. (Color online) Recording setup in the anechoic chamber. The main microphone position, 2 m in front of the sound hole, can be seen in the top right of the picture. Only this microphone (G.R.A.S. 40HL) was used in the listening tests described in this paper.

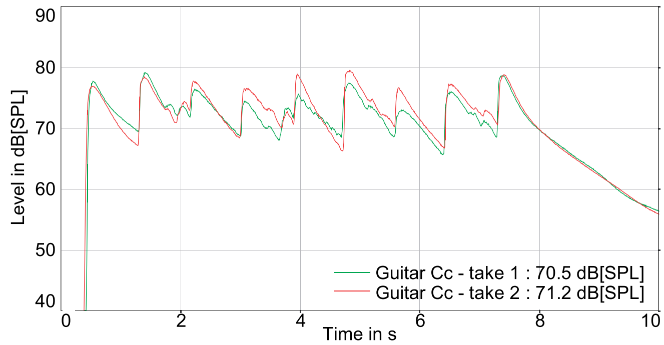

FIG. 5. (Color online) Sound pressure level vs time (fast temporal weighting) of the strumming sequence recorded twice on guitar Cc. The legend also shows the overall level for each recording.

V. LISTENING TEST

A. Setup

To investigate perceptual differences between the guitars, the recordings were reproduced in a studio room using a single loudspeaker. A Genelec 8250 A speaker was placed 2 m in front of the listener seat. The tweeter height was adjusted to 80 cm to reproduce a typical guitar position for a seated instrumentalist. The studio monitor had a flat, free-field frequency response (±1 dB from 38 Hz to 20 kHz). The volume was compensated in such a way that the speaker reproduced the same sound pressure level at the main microphone position as the original instruments in free-field conditions.

B. Participants

Twenty-three subjects (16 male and 7 female) participated in the study. Thirteen of the participants were professional guitarists with either a completed degree or studying guitar or musicology. The remaining ten participants were passionate amateur guitarists with several years of experience playing the guitar in bands. The mean age was 35.2 yr with a standard deviation of 11.6 yr.

C. Experimental design

The goal of the listening test was to identify possible preferences between the guitars. We decided to only ask for the overall preference and not ask for specific quality attributes of the guitars. This strategy was employed as an attempt to avoid influencing the participants by predefined quality categories, as is usually the case with methods applying a semantic differential. In previous experiments, the authors applied a method adapted from (ITU-R BS.1534-3, 2015) to compare musical instruments (MUSHRA). However, for subtle differences between stimuli, the International Telecommunication Union recommends applying a paired comparison method (ITU-R BS.1116-3, 2015). The recommended method was originally designed to evaluate small impairments in audio systems. In this study, the open software framework webMUSHRA (Schoeffler *et al.*, 2018) was adapted as follows for preference assessments. Please keep in mind that the applied method is somewhat different from comparing instruments in a guitar shop. Therefore, the results might not extrapolate exactly to real-life scenarios. However, this method should allow a detailed comparison of the subtle, expected differences between the instruments. To avoid participant fatigue, the two groups of guitars were pooled within the experiment. Each participant was presented with all possible pairs of the first $n = 5$ guitars in an individually randomized order. Subsequently, the paired samples from the second group were evaluated. This analysis resulted in a series of $n(n-1) = 20$ comparisons. In addition to the randomization between comparisons, the order of the presentation within each pair was randomized to prevent stereotypical responses.

All listening test sessions began with a short training phase, which consisted of two trials duplicated from the main experiment. The purpose of the training was to allow the participant to identify and become familiar with subtle differences produced by the guitars that were being tested. Two pairs of guitars were selected within each group with soundboards of the highest and lowest density (Aa and Cc and Aa′ and Cc′). During the training phase, the participants also became familiar with the test procedure: In each trial, the participants heard three recordings of the same sequence. The recordings were labeled *A*, *B*, and *C* on the video monitor screen. *A* was always the reference recording, against which both *B* and *C* were compared. However, either *B* or *C* was a repeated recording of guitar *A*—a so-called hidden reference. This hidden reference was never the exact same sound file as *A*—it was the second of the two recordings that were made with each guitar. The other sample was always from a guitar different than that played in *A*. The first task of the participants was to identify the hidden reference. Then, the participants indicated their preference for the remaining pair using a grading scale. It was emphasized during the test instructions that the grading scale had to be considered as a continuous equal interval scale with anchor points (no preference, slightly prefer, and prefer) defined at specific values. An example is shown in Fig. 6. The ratings were interpreted as numbers, with "prefer *B*" corresponding to 100, "prefer *A*" corresponding to -100 and "no preference" corresponding to 0. This number was displayed in a small box below the slider to underline the interval character of the scale.

The participants were able to switch freely among *A*, *B*, or *C* at any time, even during the playback. It was also possible and encouraged to adjust the start and end markers of the loop as preferred to focus on specific aspects of the sound. The corresponding guided user interface is shown in Fig. 7.

All audio sequences were played repeatedly until the participants were confident about their evaluations in a given trial. Completing all 20 paired comparisons took approximately 45 min.

VI. RESULTS AND DISCUSSION

The experimental design assumed that the participants could produce scores on an interval scale level (how much guitar *A* is preferred over guitar *B*). Therefore, the data were analyzed using parametric statistical testing.

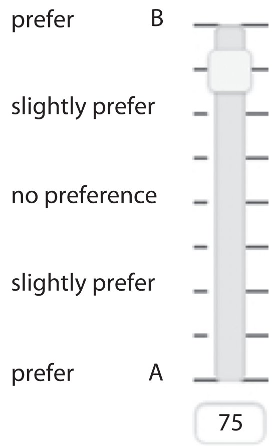

FIG. 6. Preference grading scale for the stimuli *A* and *B* with verbal anchor points.

First, the hidden reference identification discussed in Sec. V was analyzed. The listener was asked to identify the repeated recording (hidden reference) in a triad that included the paired comparison. The mean incorrect detection rate of the hidden reference was low, at 2.04 out of 20 comparisons. A binomial test confirmed with $p < 0.001$ that the correct detection rate was higher than the chance detection rate. This finding suggests that the participants were able to reliably distinguish the differences between guitars. The absolute preference scores for all participants and all pairs of the first group of five guitars (variable bracewood and soundboard) and the second group (variable soundboard only), can be found at https://doi.org/10.17605/OSF.IO/QK5VE. The individual paired-comparison scores can be used to derive mean values, which are presented in matrix form in Tables II and III. Positive scores indicate that the guitar in the column was preferred to the guitar in the row.

For the following parametric statistical analysis, the software package "Statistical Package for the Social Sciences" by IBM was used. The presence of a normal distribution was tested with the Shapiro–Wilk test because of the small sample size (23 test participants). Fifteen of 20 pairwise ratings showed significance above 0.05, meaning that normal distributions could be generally assumed.

Some tendencies can already be suspected from the averaged pairwise data in Tables II and III. However, for statistical

FIG. 7. (Color online) Graphical representation of the strumming sequence with the adjustable start and end markers of the loop. The same image of the waveform was used for all stimuli.

TABLE II. Mean preference score matrices for guitars with variable bracewood and soundboard. Positive values mean that the guitar in the column was preferred to the guitar in the row.

Score	Aa	Ab	Bb	Cb	Cc
Aa	—	−3	−4	−12	−51
Ab	3	—	1	−14	−37
Bb	4	−1	—	−8	−4
Cb	12	14	8	—	6
Cc	51	37	4	−6	—

analysis, it is meaningful to employ individual ratings and average scores for each guitar. To obtain an averaged preference score for each guitar (e.g., guitar Aa), the mean of the pairwise scores (e.g., guitar Aa compared to all others: AaAb, AaBb, AaCb, and AaCc) was calculated for each guitar and each participant as follows: the averaged rating for guitar Aa = (AaAb + AaBb + AaCb + AaCc)/4. The presence of a normal distribution was again tested with the Shapiro–Wilk test because of the small sample size (23 test participants). All averaged ratings showed a normal distribution.

A repeated-measures analysis of variance (ANOVA) was applied for the statistical analysis of the preference data for the first group of instruments with varying soundboards and bracewood. The influence of the within-subject factor, the guitar, and the two between-subject factors, gender, and expertise, on the averaged instrument scores was evaluated. The guitar factor included five levels (Aa, Ab, Bb, Cb, and Cc), expertise included two levels (professional guitarist and amateur guitarist), and gender included two levels (male and female). The detailed ANOVA results can be found at https://doi.org/10.17605/OSF.IO/QK5VE including the full dataset. Mauchly's test indicated that the assumption of sphericity was violated for the main effect guitar [$\chi^2(2) = 24.96$, $p = 0.003$]. Therefore, the degrees of freedom were corrected using Greenhouse–Geisser estimates of the sphericity ($\varepsilon = 0.65$). The resulting ANOVA revealed that there was a highly significant difference between the instrument scores [$F(2.61, 52.14) = 5.04$, $p = 0.006$]. No between-subject effects or interaction effects between the instrument scores and gender or expertise were significant. This result suggests good agreement between the participant groups. The averaged preference ratings are plotted with 95% confidence intervals in Fig. 8. To explore the significant main effect, *post hoc* pairwise comparisons were conducted using the Bonferroni correction for multiple comparisons. Guitar Aa was preferred very significantly to guitar Cc (average difference = 40.57, $p < 0.001$), and guitar Ab was preferred significantly to guitar Cc (average difference = 34.96, $p = 0.036$). Guitar Cc was made from wood at the high end of the E_L scale that had a high density. Guitars Aa and Ab were made with wood at the other end of the E_L scale. Guitar Aa was made of wood that had a low density, and guitar Ab was made with wood that had a median density. The results suggest that a low E_L and low (or median) density were preferred over a high E_L and high density regarding the selection of wood for the soundboard and bracing.

TABLE III. Mean preference score matrices for guitars with a variable soundboard only. Positive values mean that the guitar in the column was preferred to the guitar in the row.

Score	Aa′	Ab′	Bb′	Cb′	Cc′
Aa′	—	4	2	−17	−51
Ab′	−4	—	0	−31	−16
Bb′	−2	0	—	−8	−3
Cb′	17	31	8	—	−40
Cc′	51	16	3	40	—

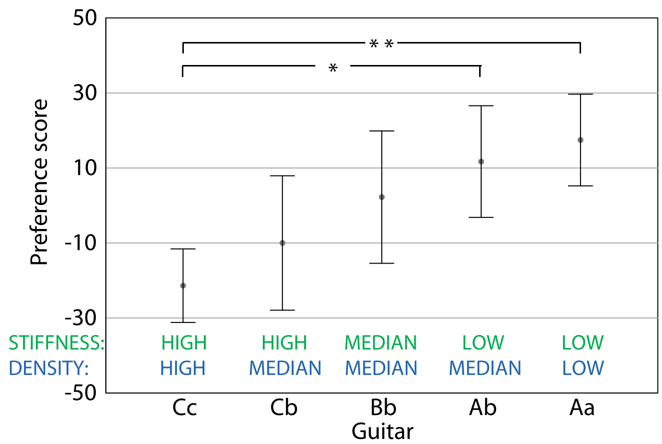

FIG. 8. (Color online) Mean preference evaluation for all guitars with varying bracewood and soundboards plotted with 95% confidence intervals. Guitars Aa and Ab were judged to be statistically significantly better than guitar Cc.

To investigate the effect of varying E_L alone while keeping the density constant, guitars Cb, Bb, and Ab were compared. The corresponding ratings show larger confidence intervals, indicating a stronger disagreement between participants regarding preference compared to guitars Aa and Cc. However, there seems to be an overall (not significant) tendency of increasing preference for decreasing E_L, which is consistent with the previous conclusion.

Figure 9 shows the separate results for the professional and amateur guitarists. The amateur guitarists tended to show

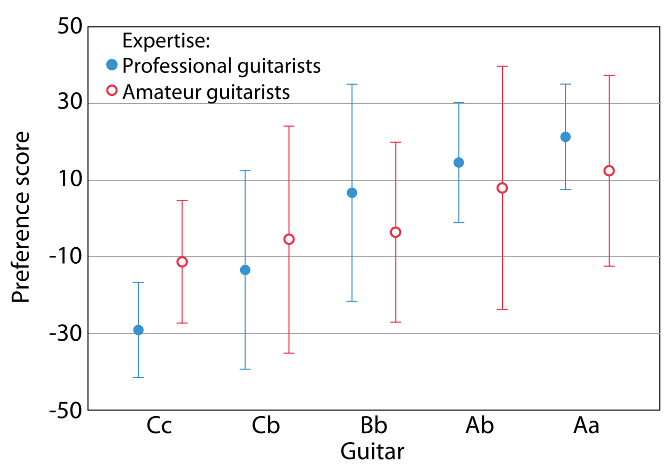

FIG. 9. (Color online) Mean preference evaluation for all guitars with varying bracewood and soundboards plotted with 95% confidence intervals. The results for the professional guitarists are plotted with closed symbols, and the scores from the amateur guitarists are plotted with open symbols.

slightly less discrimination between the guitars. However, as was already reported, this difference was not statistically significant.

Another repeated-measures ANOVA was applied to analyze the preference scores of the second group of instruments (varying soundboards but constant bracewood at median values). Mauchly's test indicated that the assumption of sphericity was not violated for the data, so no correction was applied. Again, a highly significant difference between the instrument scores was found [$F(4, 80) = 7.51$, $p < 0.001$]. No between-subject effects or interaction effects between the instrument scores and gender (male vs female) or expertise (professional vs spare-time guitarist) were significant. The averaged preference ratings are plotted with 95% confidence intervals in Fig. 10. To explore the significant main effect, *post hoc* pairwise comparisons were conducted using the Bonferroni correction for multiple comparisons. There was a very significant preference for guitar Ab′ over guitar Cc′ (average distance = 44.12, $p = 0.002$) and for guitar Aa′ over Cc′ (average distance = 50.35, $p = 0.001$). Additionally, guitar Aa′ was significantly more preferred than guitar Cb′ (average distance = 24.12, $p = 0.026$). It is apparent that the ranking of the guitars in the second group is identical to that in the first group. The low-E_L guitars Aa′ and Ab′ were preferred to the high-E_L guitar Cc′. There is a natural correlation with density: guitars Aa′ and Ab′ are made of low- and median-density wood, respectively, whereas the soundboard of guitar Cc′ is made of high-density wood. The results confirm the finding that low-E_L and low- (or median-) density soundboard wood were preferred over a high E_L and a high density. This was true whether the bracewood co-varied with the soundboard (group 1) or was maintained at median values (group 2). Additionally, a low E_L and a low density were preferred over a high E_L and a median density. Varying E_L alone while keeping the density constant by comparing guitars Ab′, Bb′, and Cb′ again showed no significant differences. However, the tendency in the ranking of slightly greater preference with decreasing E_L can be guessed from the mean values. The same tendency was already apparent in Fig. 8.

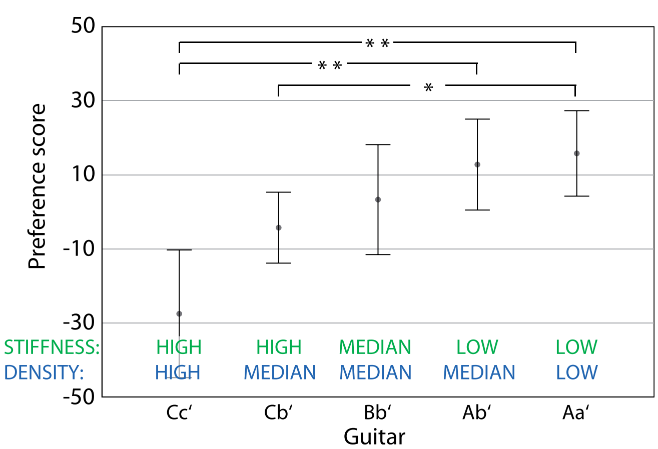

FIG. 10. (Color online) Mean preference evaluation for all guitars with variable soundboards only plotted with 95% confidence intervals. Guitars Ab′ and Aa′ were judged statistically to be significantly better than guitar Cc′. Additionally, guitar Aa′ was judged to be significantly more preferred than guitar Cb′.

TABLE IV. Stress and R^2 values for MDS solutions for both groups of guitars.

Group with variable	Dimensions	Stress	R^2
Bracing and soundboard	1	0.70401	0.70401
	2	0.09892	0.90042
Soundboard only	1	0.36822	0.45505
	2	0.05523	0.96534

Preference data, by themselves, do not indicate which perceptual criteria were employed by the listener to derive a preference for one guitar over another. These criteria can be studied, however, by considering them as perceptual dimensions, using the statistical technique of multidimensional scaling (MDS). In MDS, stimuli are placed in an N-dimensional space usually based on a matrix of dissimilarity ratings between pairs of stimuli. In Sec. VII, we attempt to use the preference distances from the current study to assign coordinates to the guitars in a multidimensional space. Accordingly, a metric MDS was calculated using the mean preference score matrices listed in Tables II and III. Euclidean distances were selected as scaling models. To determine the amount of variance, the scaled data could be accounted for by the MDS procedure, and an R^2 value could be calculated. Larger R^2 values are better. Additionally, stress values were calculated using Kruskal's formula (1). The lower the stress value is, the better the solution. The resulting values are shown in Table IV for both groups of guitars. When trying to scale the data with one dimension only, high stress values are obtained, indicating a poor representation of the data by the model. Much lower stress values were found when introducing a second dimension, improving the goodness-of-fit. The resulting R^2 value in the two-dimensional case is greater than 0.9 in both groups. It is concluded that the assumption of two underlying perceptual dimensions helps to explain the preference results.

The resulting configurations for both MDS models are shown in Figs. 11 and 12. It is apparent that the two independent dimensions show some correlation with the two physical variables modified in this study. Increasing E_L can be followed in the vertical direction along the line of guitars Ab, Bb, and Cb in Fig. 11 and slightly more obviously along

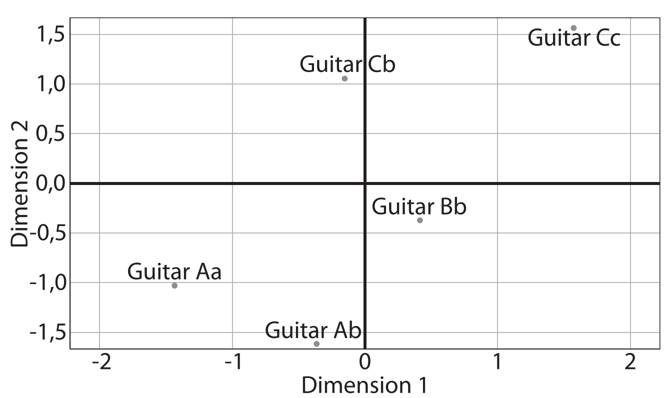

FIG. 11. Multidimensional scaling configuration using Euclidean distances between the stimuli based on the averaged preference ratings for guitars with varying bracewood and soundboards.

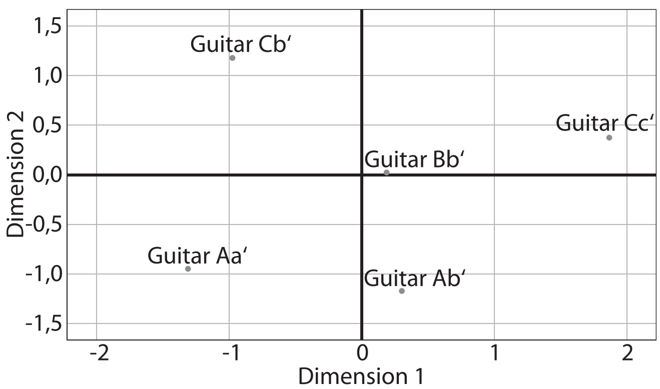

FIG. 12. Multidimensional scaling configuration using Euclidean distances between the stimuli based on the averaged preference ratings for guitars with varying soundboards only.

the line of guitars Ab′, Bb′, and Cb′ in Fig. 12. Increasing density (and E_L) can be followed in the horizontal direction along the line of guitars Aa, Bb, and Cc in Fig. 11 and along the line of guitars Aa′, Bb′, and Cc′ in Fig. 12. It is noteworthy that the scaling using perceptual data can be mapped directly to material characteristics. This result suggests that both physical parameters influence independent perceptual attributes.

VII. CONCLUSIONS

This study examined the relationship between the acoustic characteristics of a guitar top, namely, longitudinal E_L and wood density, and the resulting sonic quality of a steel-string guitar. Nine Taylor 814ce guitars were produced with high control over all the production parameters. The backs/sides, bridge, and neck were built from a measured population of wood with mean density values measured for the components. However, the longitudinal E_L and density values varied for the top (soundboard and bracewood). A short music sequence was selected and recorded by a real musician in an anechoic chamber. The resulting stimuli were compared in pairwise listening tests, and the participants were asked to rate their preference. No other perceptual attributes were evaluated to avoid influencing the participant's preference criteria. The statistical analysis of the data resulted in two interesting outcomes. First, the participants were able to distinguish the differences between different guitars from differences between the recordings. Second, the guitars with a low E_L and a low (or median) density were significantly preferred over guitars with a high E_L and a high density of the top wood. The general trends were the same if the soundboards and bracewood or soundboards only were varied. The results allow for the selection of the optimal top wood for the given model of a popular guitar. However, more generally, they provide an example of the importance of integrating the design with physical characteristics of the component wood. Similar examples can be found in studies of classical guitars (Baltrusch, 2000; Ziegenhals, 2001). Furthermore, a MDS analysis revealed that both physical parameters (E_L and density) seemed to influence independent perceptual preference attributes.

In a future study, an attempt could be made to correlate physical measurements with the perceptual results presented here. Therefore, vibration measurements of the soundboard and acoustical measurements of the radiated sound should be analyzed. In this process, a controlled and reproducible excitation of the guitar is extremely important. Understanding the link between physical sound generation and perceptual attributes provides a valuable tool to build the best musical instruments.

To make the result more universal, the study should be repeated for other guitar designs. The combined effect of different influencing factors, e.g., the musician, room, or selection of the music sequence, can be investigated by integrating these factors into the experimental design. The influence of other physical parameters of the top wood (e.g., damping) is another open question at present.

ACKNOWLEDGMENTS

This research was supported by PRT and Taylor Guitars. We thank Steve McMinn and Eric Warner for initiating this study and Bob Taylor and Andy Powers for their open mindedness and precise manufacturing of the guitars. We would like to thank Judith Beckedorf and Peter Groesdonk for the careful recording sessions and Margitta Lachmann who conducted many listening tests. We are also grateful to all the participants who participated in this study. We thank the associate editor and the anonymous reviewers for their valuable comments. The guitar recordings and the full data from the listening test are available at https://doi.org/10.17605/OSF.IO/QK5VE.

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