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Revisiting the Notion of “Resonance Wood” Choice: A Decompartmentalised Approach, from Violin-Makers’ Opinion and Perception to Characterization of Material Properties’ Variability

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Abstract

This work aims to improve our understanding of the resonance wood and to investigate the interactions between their physical-mechanical properties, natural variability, and the violin-makers’ ways of choosing their materials. In order to identify luthiers’ practices and opinions, a socio-technical survey was conducted. Physical, vibrational, and visual/structural characteristics of the resonance wood obtained from several provenances with a variety of quality grades were also determined. Finally, these two approaches were completed by a psychosensory evaluation to compare the measurements that we have conducted with the perception and qualification of wood by the violin-makers.

1. Introduction

Woods, as the main constitutive materials of many musical instruments, play an essential role in defining their “identity”. The choice of wood by instrument-makers is, therefore, a central question. It is intricately linked with the flora available (local or imported), cultural aspects of both woodworking craftsmanship and aesthetics (musical and visual), as well as physical behaviour and the acoustic response resulting from the material-structure-excitation system. This means that the study of instrument-making wood is intrinsically linked to the notion of diversity, whether biological, cultural, functional or physical diversity, or all of these together. It also means that various different disciplines, often very distantly related to each other, may be involved in the study of wood choice by instrument-makers. However, most existing research usually adopts a single or limited number of viewpoints.

In some of our previous work, we aimed at relating biological and cultural diversity together with material physical/acoustical properties, in order to understand wood choice through different geocultural areas (for tuned idiophones’ bodies or for chordophones’ soundboards [1]), or through centuries (for European bows [2]). However, when one tries to consider jointly all the above-cited types of diversity together, some information is often missing, from at least one of the involved disciplines or viewpoints. Especially, it seems that extra-European instrument-making cultures have benefited from less academic research than Western ones did, and early-music (or traditional) instrument-making less than Classical or modern ones. Direct interaction with instrument-makers from the various cultures is also more difficult (or even impossible for past cultures). Similarly, tropical, Mediterranean, or even temperate but “secondary” forest species have benefited from much less physical characterisation of their woods than did more common temperate hardwoods and especially softwoods. Therefore, in order to better understand the concept of “choice of wood by instrument-makers”, with enough precision and information within and between the different fields involved, it may be useful to focus and reduce the object of study while keeping the variety of viewpoints [3]. It is then necessary to select a case study which is sufficiently documented in different disciplines, in order to serve as a model for a decompartmentalised approach.

Among the many instrument-making woods or tonewoods around the world, the term “resonance woods” usually refers to those employed in the making of the violin family [4, 5, 6, 7]. The choice is nearly exclusive to spruce (usually *Picea abies*) for the soundboard and to maple (usually *Acer pseudoplatanus*) for the back and sides. Due to the cultural importance and the “prestige” of the violin in Western classical/academic music, the instruments themselves, and the woods used for mak-

ing them, have been the subject of extensive research, in organology/musicology, acoustics, and forestry/wood science, much more than any other type of instrument-wood association. As an example, the sole *Picea* genus (spruce) is described by a number of tests for vibrational properties that is as big as the total number of such tests for all species (several tens of thousands) from tropical forests... [8]. And yet, the actual span and different scales of variability within spruce resonance wood have still not been completely assessed. There are also several technical treatises of violin-making from the two past centuries which describe some criteria for choosing wood [7, 9]. Most importantly, violin-making encompasses a wide and vivid community of active luthiers, and, so it seems, a quite strong transmission of craftsmanship knowledge with little discontinuities can be observed. Therefore, the violin-makers’ choice for resonance wood would give us a good model for studying the different facets involved in the choice of wood for musical instrument-making. However, most research has remained quite compartmentalized, with little integration between information from different disciplines, and even less so between scientific and craftsmanship knowledge. In addition, a possible pitfall to watch for within this subject is that the prestige of the violin has generated a certain number of myths conveyed to the general public [10]. This is outside the subject of our work, but it suggests that resonance wood selection merits study with a pair of fresh eyes.

The general objective of this research is therefore to revisit the concept of “resonance wood choice” by taking jointly into account the opinion and practice of violin-makers, the characterisation of physical-mechanical properties according to several scales of wood variability, and the sensory perception by makers in order to determine the relationships between the craftsmanship experience and the quantifiable properties of wood.

2. A Survey to Grasp Luthiers’ Opinions, Practices and Craftsmanship Knowledge on Wood

Although some aspects of wood choice by violin-makers are written in early technical treatises and reviews [7, 9], very little formal research has been conducted recently to grasp the opinion of contemporary instrument-makers. One of the rare examples of a recent survey with violin-makers, in the field of anthropology of techniques, examines the learning process and the transmission of the knowledge of the trade [11], but it seems that the knowledge of the wood itself was not specifically addressed in such surveys.

To improve our knowledge of violin-makers practices and their main issues and opinions about wood, we created a specific survey [9,

12, 13]. The questionnaire was first designed for face-to-face interviews, following a modular structure, and then put online. It contains nine sections organized as follows:

- a. profile of the interviewee
- b. concept of the 'quality' of an instrument
- c. supply & wood choice in general
- d. evaluation of wood for top plates
- e. evaluation of wood for back plates
- f. evaluation of wood for bows
- g. aging, treatments and varnishes
- h. link to scientific and historical research
- i. questions, feedback and comments.

The objective is to capture how luthiers consider the role of wood in the quality of violin and their procedure for obtaining wood supplies, as well as to categorize the different criteria they rely on for the selection of wood blanks.

The analysis of the survey is currently based on 15 complete responses of makers of the bowed-strings family. All of the participating craftsmen are French and produce string quartet instruments (violin, viola and cello, with less than one fourth working on double-bass). Two of them are also luthier-bow makers, and another two also build early-music instruments (viola da gambas or early bows). Almost all of them are independent craftsmen. The majority (64%) of the makers work alone in their workshop. The average age of respondents is 46 years. Thus, the panel's experience distribution between the classes (less than 4 to 37 years) is balanced, with a majority having more than 15 years' experience. The panel of respondent luthiers are primarily engaged in the construction of new instruments (60% of their time, on average).

The approaches that luthiers reckon to use during their work are "principally" or "often" (85%) empirical (know-how and technical knowledge) followed by historical (70% "often") but scientific approaches are only "moderately" or "little" (79%) used in daily work. Meanwhile, most of these makers reported a lot of interest for scientific research on instruments (76%) and/or on tonewood (83%). Individual makers show various "profiles" of interest between several fields of academic research (humanities and arts, natural or physical sciences), and many of them (70%) consider that they conduct research in their workshop.

According to the luthiers interviewed, the choice of wood for top and back plates ranks within the top most important making parameters that determine the quality of an instrument. For "overall quality", they consider the wood for back plate to rank first (100% "very important" or "important") followed by varnish and wood for top plate (93% each).

For "sound quality", too, the choice of wood for the back comes first, tied with fine adjustments (100% "important/very important"), and the wood for the top plate comes second (93%), that is, even before important structural making parameters such as design, geometry and pre-stresses (86% each).

Most of the makers (80%) buy the wood for top and back-plates from specialized suppliers of tonewood. They generally acknowledge their suppliers' expertise and thus trust in their work and preselection of wood. While the luthiers are interested in the forest dimension, they do not consider themselves competent enough and/or do not have time to delve more deeply into it. This was confirmed by an interview with a supplier, who stated that makers are not interested enough to go to the forest. Some of the makers have also evoked the image of luthiers prospecting wood directly in the forest as a myth, but one that they take pleasure in maintaining.

The two most important criteria in the purchase of wood supplies by luthiers are the quality followed by price. The provenance and the drying time of the offered stocks have only secondary impact on the choice of suppliers, but the traceability of their stock has also sometimes emerged spontaneously. Moreover, suppliers also evoke an increase in makers' expectations. Previously, suppliers only proposed two categories of wood blanks to the makers based on their quality (one priced at €30, the other at €50). However, nowadays they have to offer a wider range of products with prices ranging from €10 to €300. For spruce wood used for top plates, three main provenances were mentioned by the makers: Italy ("Val di Fiemme", "Italian Alps", "Italian Dolomites"), Switzerland ("Tyrol", "Swiss Alps") and France ("Jura", "French Alps"). This is consistent with the spruce tonewood repartition area but does not cover all the known provenances of such wood. French makers mainly focus on the historical cradle of violin-making and on the West part of tonewood repartition area, the nearest to them. For maple, the stated degree of precision for provenance varies greatly (from "indifferent" or "Europe" to specific countries), with "the Balkans" being the most cited.

When choosing wood from the stock of a given supplier, interviewed makers rely mostly on their experience, on a "feeling acquired by practice" for evaluating wood quality, and only very little on "rules from training or books" or "measuring tools". To guide their selection of wood pieces, they mostly use their personal evaluation of visual features (83% "very important" + 17% "important") and weight/density (75% "very important" + 25% "important"), while hand testing of acoustic features like "tap-tone" is stated as "important" (42%), but less strongly relied on (only 42% "very important"). Their choice is based very little on measuring tools (only 17% "important") or quality grades attributed by suppliers (only 17% "important").

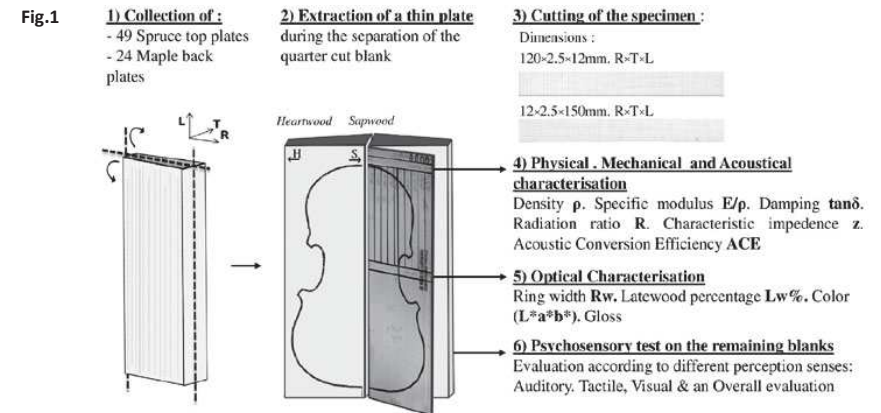
Concerning the choice of individual wood blanks (wedge shaped boards) for top plates, the selection criteria for spruce are mainly based, by order of stated importance, on the cutting plan/orientation (importance score 9.7/10), density (8.8), growth-ring uniformity (8.3) and width (8.0), percentage of latewood (8.3), and hardness (8.0). All other stated criteria, including “tap-tone”, get importance scores lower than 7.0/10. For maple wood for back plates, the cutting plan also appears to be the most important criteria (8.5/10), followed by growth-ring width (8.0) and density (7.6), medular rays (7.1), and then figure (6.9). The cutting plan evaluation for both the top and back plates is considered as “very important” or “important”, which might suggest a good perception of the mechanical performance of wood by the makers, since a minor change of grain angle is enough to greatly affect vibrational properties [14]. Most of the luthier’s panel admit that they have changed over time, at least slightly, their criteria for choosing a wood blank.

3. Material Properties and Natural Variability of Resonance Woods

3.1 Characterisation of the Physical, Mechanical, Acoustical and Structural Properties

A wide sampling of wood sold for violin plate blanks (wedge shaped boards) was collected from different suppliers and provenances, with varying quality grades. Regarding the spruce, 49 top plates were gathered from three different provenances (France, Italy, Switzerland) and four quality grades (from the lowest, D, to the highest, A, quality grade). The selection of top plate blanks was not meant to be representative of a supplier’s stock but, instead, to represent the maximum variability that could be offered. Similarly for maple, 24 blanks for back plates and sides were procured from four quality grades established by the suppliers, aiming to take into account the highest variability. One of the main selection criteria was the variety of wavy grain figures.

The sampling plan and specimen cutting protocol [Fig.1] aims at improving the knowledge of the multi-level variability of resonance wood properties, jointly with a study of makers’ perceptive evaluation (see section 4). Compared to most other existing studies, here we also included an additional variability factor: the local variations of properties within a given wood blank. A thin board (2.5 mm in thickness) was extracted during the separation of the quarter cut blank wedge into two halves of the future top (soundboard) or back plate. These thin boards, representative of the initial violin-making blank wedges, were used for laboratory testing, while the remaining wedge blanks were kept for the psychosensory evaluation. Radial (*R*) and longitudinal (*L*) specimens were cut from the thin boards to assess the properties of the wood and their variations in those two directions. From each thin board, one to



three radial specimens with the dimension of 120 mm × 2.5 mm × 12 mm (*R* × *T* × *L*) and seven to ten longitudinal specimens with the dimension of 12 mm × 2.5 mm × 150 mm (*R* × *T* × *L*) were obtained. They were conditioned at 20±1 °C and 65±2% RH for at least 3 weeks to reach the standard air-dry equilibrium moisture content (~12%). These specimens were characterized for their physical and vibrational properties (density ρ , specific modulus of elasticity E'/ρ , damping coefficient $\tan\delta$, in *R* and *L* direction, and also shear properties G_{LT} and $\tan\delta_{GLT}$ on a sub-sampling), and their optical/structural traits (ring width Rw , latewood percentage $Lw\%$, colorimetry, gloss) as described in [9]. Then some acoustic “performance indexes” described in [1, 15-17] were calculated (radiation ratio $R = c/\rho$, characteristic impedance $z = \rho E$, acoustic conversion efficiency $ACE = R/\tan\delta$ and loudness index $L = R_L R_R / \delta_L \delta_R$).

The summary of all measured properties of spruce and maple resonance wood (calculated by averaging values of the different specimens cut from a given plate) is provided in **Table 1**. The values of the measured properties are consistent with other studies [4, 5, 6, 16, 17, 18], even if sometimes the ranges of variation that we observe are higher, as a result of our wide sampling.

Fig.1 General sampling plan, specimen’s cutting and test protocol.

Table 1

		Spruce						
		Min	Max	Av.	S. Er.	Rov (%)	Cov (%)	Nb
Mechanical vibrational properties	ρ	0.32	0.55	0.42	0.06	56	13	49
	E_L / ρ	18.5	35.9	29.7	3.3	59	11	49
	E_R / ρ	1.2	3.4	2.3	0.4	95	18	49
	$\tan\delta_L$	0.006	0.010	0.007	0.001	53	11	49
	$\tan\delta_R$	0.017	0.036	0.022	0.004	90	19	49
	E_L	6.3	17.0	12.4	2.6	87	21	49
	E_R	0.5	1.4	0.9	0.2	90	21	49
	G_{TL}	0.70	1.22	0.93	0.16	55	17	9
	$\tan\delta_{GTL}$	0.016	0.020	0.018	0.001	17	6	9
Acoustical indexes	z_L	1.5	3.1	2.3	0.4	71	17	49
	z_R	0.4	0.8	0.6	0.1	64	15	49
	R_L	9.7	16.6	13.3	1.5	52	12	49
	R_R	2.3	5.5	3.7	0.6	88	17	49
	ACE_L	1241	2628	1938	320	72	16	49
	ACE_R	92	277	178	45	104	25	49
	L	16505	71047	35300	12356	155	35	49
Optical features	Rw	0.77	2.52	1.48	0.37	118	25	45
	LW %	0.13	0.26	0.18	0.03	77	16	45

		Maple						
		Min	Max	Av.	S. Er.	Rov (%)	Cov (%)	Nb
Mechanical vibrational properties	ρ	0.5	0.7	0.6	0.0	25	7	24
	E_L / ρ	11.1	20.7	15.3	2.7	63	18	24
	E_R / ρ	1.9	3.1	2.7	0.3	45	11	24
	$\tan\delta_L$	0.01	0.01	0.01	0.00	53	16	24
	$\tan\delta_R$	0.02	0.03	0.02	0.00	21	6	24
	E_L	6.7	13.8	9.8	1.8	73	19	24
	E_R	1.2	2.1	1.7	0.2	51	13	24
	G_{TL}	1.2	1.6	1.4	0.1	27	8	8
	$\tan\delta_{GTL}$	0.017	0.028	0.021	0.003	53	15	8
Acoustical indexes	z_L	2.2	4.5	3.4	0.7	68	20	24
	z_R	0.8	1.7	1.3	0.3	68	22	24
	R_L	4.8	7.6	6.1	0.7	45	12	24
	R_R	2.1	3.2	2.6	0.2	40	10	24
	ACE_L	352	870	598	148	87	25	24
	ACE_R	83	153	116	16	60	14	24
	L	3458	12498	7095	2460	127	35	24
Optical features	Rw	-	-	-	-	-	-	-
	LW %	-	-	-	-	-	-	-

Table 1 Summary of characterizations at the blank plates' level of spruce and maple resonance wood. Av: Average; S.Er: Standard error; Rov: Range of variation; COV: Coefficient of variation; Nb: Number of Top or Back plates; L: Longitudinal direction; R: radial direction; T Tangential direction.

In spruce, we notably observe a large range of density ρ (0.32 to 0.55), specific modulus of elasticity in the longitudinal direction E'_L/ρ (18 to 35 GPa), longitudinal damping factor $\tan\delta_L$ (0.006 to 0.100), ring width Rw (0.77 to 2.52 mm) and latewood percentage $Lw\%$ (13 to 26%). The expected properties for spruce, such as low damping coefficient ($\tan\delta$), low characteristic impedance (z), high axial specific modulus (E'_L/ρ) and high radiation ratio (R) were considered together with the role of the top-plate soundboard in the instrument (for instance, the higher the radiation ratio is, the greater the vibration amplitude and radiation will be).

Regarding maple wood for back plate, its range of variation (Rov) of the properties appears to be lower than the spruce's, which is probably due to, partly at least, the lower number of boards studied, for the coefficients of variation (Cov) are of comparable amplitude for the 2 species. As expected, maple specimens possess higher density, damping and characteristic impedance, while having lower specific modulus, radiation ratio and ACE than spruce. The measured properties of spruce and maple present specificities adapted to their role in the instrument making [15, 17, 19]. Some current studies have taken into account these differences in wood properties in the modelisation of violins in order to quantify the respective impact of various wood parameters on the vibroacoustic response of the instrument [20].

3.2. Natural Variability of Properties Between Different Violin-Making Wood Blanks

In this part, we will focus on spruce since the variability of maple properties was previously analysed in regards to its anatomical features in our recent paper [21]. Our general objective is to evaluate the variability of physical and acoustical properties of tonewood in relation to qualities for use. Fig.2 shows, for a given property, the differences between quality grades and whether or not they are significant using the Multiple Comparison test. We observed that the differences

Fig.2

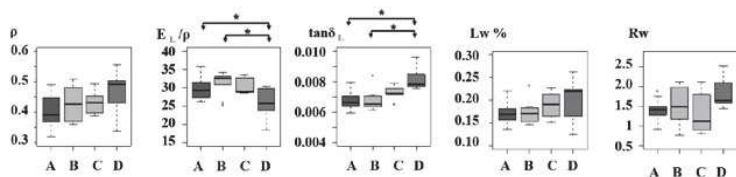


Fig.2

Distribution of some physical-mechanical properties and optical features of resonance spruce plates according to different quality grades (A=highest, D=lowest): the significance of differences between grades is indicated by a star (*).

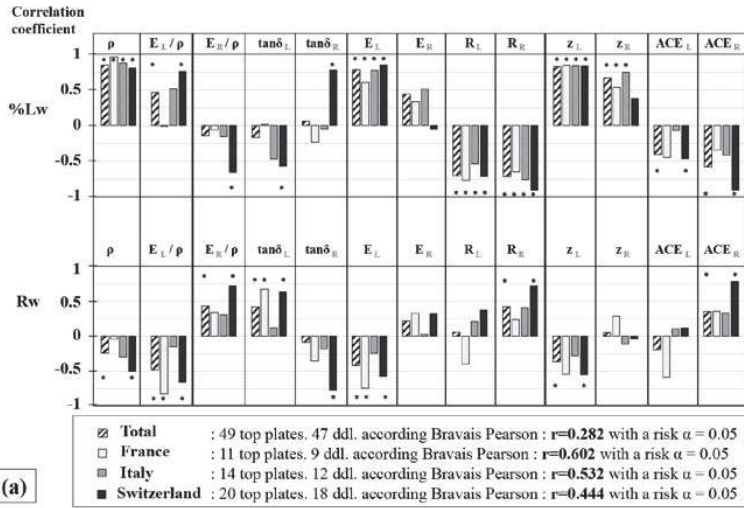
between the first and second quality grades were not significant, whereas significant differences were found on the fourth quality grade, which clearly differs from other grades. However, even without statistically significant differences between suppliers, clear trends can be observed among the four quality grades: with the increase in quality grade, we found lower density (ρ), higher specific modulus (E'_L/ρ), lower damping ($\tan\delta_L$), and lower latewood percentage ($Lw\%$) and ring width (Rw) within the resonance wood. Those observations are consistent with current makers' selection criteria and previous research, which, however, included fewer quality grades [18].

It is also interesting to compare those results with the survey: although makers claimed their trust in their supplier's expertise, they also said that they paid little attention to supplier grades. We could explain this paradox with the following assumption: suppliers sort resonance woods mostly on cutting, optical, and density criteria, which seems to also lead to a mechanical and acoustical sorting. However, the distribution of properties within each grade shows that it is indeed possible to find adequate resonance wood in other grades than the first one. Considering the fact that the quality grades also affect the prices, one can propose a hypothesis that the makers' behaviour on quality grades attributed by suppliers, is mostly guided by economic reasons.

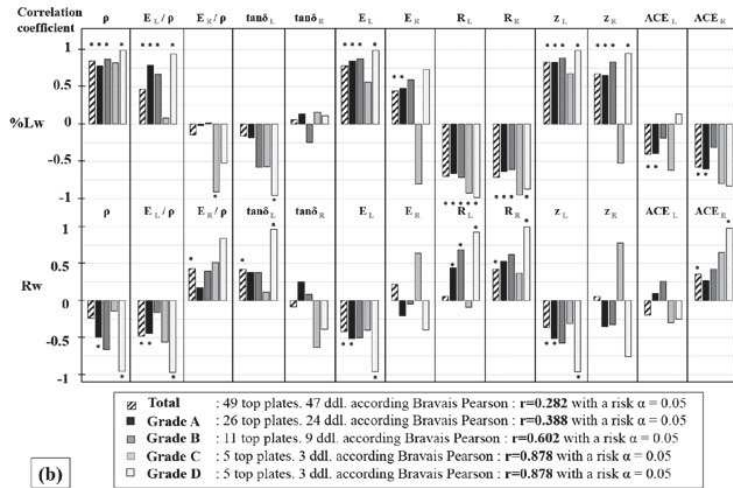
To complete our understanding of the variability between different wood blanks, the correlation between optical-structural characteristics (latewood percentage and ring width) and physical-mechanical properties or acoustical indexes is represented according to wood provenance and quality grade in Fig.3. Latewood percentage highly correlates with wood density (ρ) and acoustical indexes such as radiation ratio (R) and impedance (z) in both longitudinal and radial directions for the three provenances and the four quality grades. Concerning ring width (Rw), its correlations with other properties is weaker; however, ring width seems to be a good indicator of specific modulus (E'_L/ρ) in the longitudinal direction. This last result, obtained from spruce specimens that have been pre-selected as resonance wood, is interesting because such a correlation barely exists in general supply (non-selected wood) or faster grown trees of the same species [22].

However, there are clear differences in these correlations depending on provenance. For example, while it seems that the ring width of the wood samples from Italy do not share any relationships with any properties for wood samples from France and Switzerland, the ring width correlates with longitudinal specific modulus, damping, and anisotropic ratios. Further, the relationships between latewood and specific modulus also differ according to each provenance. As an example, the correlation is highly significant for top plates from Switzerland but non-existent for those from France.

Fig.3



(a)



(b)

Fig.3 Correlations between visual features and mechanical and acoustical properties according to top plate provenance (a) and quality grade (b). The significance of correlations is indicated by a star (*).

To sum up, instrument makers' criteria for visual evaluation seem to give us an idea of some of the physical/acoustical properties of wood, even if those relations are not always equal for every provenance and quality grade of the wood.

3.3. Variations within individual blank wedges of resonance spruce

Within-plate variations of wood properties, corresponding to different radial positions, are shown in **Table 2**. Although the mean level of variability (ROV or COV) is smaller within one plate than between different plates (**Table 1**), the maximum coefficient of variations behaves differently. Within-plate variation is equivalent to between-plate variation for longitudinal specific modulus (11% in both cases) and even significantly higher for latewood (28% vs. 16%) and ring width (39% vs. 25%). For some properties, a higher variability can be observed within some given plates than between the different plates. These results suggest that, in resonance wood study, intra-plate variations must be considered almost at the same level as the inter-plate variations, even if the amplitude depends on the studied plate.

Table 2

		Rov	Cov
ρ	Average	11%	4%
	Min	3%	1%
	Max	24%	7%
E _L /ρ	Average	13%	4%
	Min	4%	2%
	Max	34%	11%
tanδ _L	Average	14%	5%
	Min	4%	1%
	Max	26%	11%
Rw	Average	63%	20%
	Min	27%	8%
	Max	110%	39%
Lw %	Average	32%	10%
	Min	11%	4%
	Max	96%	28%

Table 2 Variation within one spruce top plate of wood properties and optical features. Rov: Range of variation = (max-min)/average; Cov: Coefficient of variation = standard deviation/average.

Fig.4

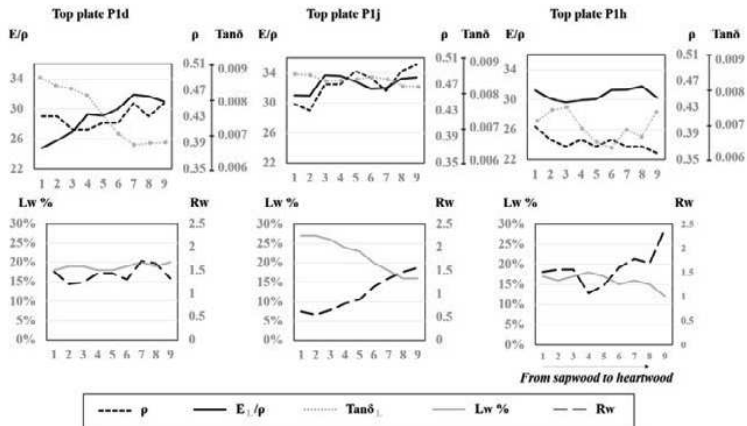


Fig.4 gives the radial variation of the main properties and characteristics: density (ρ), specific modulus (E'_L/ρ), damping ($\tan\delta_L$), ring width (Rw), and latewood percentage (Lw, %). They are shown from outerwood (closer to sapwood) to innerwood (towards centre of the tree), corresponding to the center and the side, respectively, of the top plate of a musical instrument such as a violin. From the center to the side (of a future soundboard), different trends are observed according to the property: generally an increase of specific modulus and ring width, and a decrease in density, damping and latewood percentage. However, the existence of marked heterogeneity, both concerning the profile and the amplitude of variations, can be noted depending on the wood plate.

During the survey, some makers indicated a preference for resonance spruce with thinner rings in the center of the instrument (0.8 to 1.5 mm) and wider rings in the sides (2.0 to 2.5 mm). From our previous observation, one can wonder: what is the impact of the selection criteria based on ring width on the material properties? The intra-plate variability has to be taken into account since the overall characterisation of the board does not provide enough information on wood properties and their variations, and one unique sample from the board may not be representative of the top plate properties.

Fig.4 Representation of the intra-plate variability of some wood properties and optical features. The top plates presented here (P1d, P1j, P1h) belong to top quality grade A.

4. Sensory Perception of Resonance Spruce

In the previous sections, we studied tonewood selection from several viewpoints, but there was no direct confrontation between the makers, the material, and its measured variability. In this part of our work, we aim to understand the direct interactions between the craftsmen and their wood through a psycho-sensory evaluation. There are few studies on the sensory perception of wood by instrument-makers (e.g., [23]), with, to our knowledge, only one focusing on violin-making resonance wood [6], while it is suggested that trade-speciality strongly impacts wood perception [24].

As the perceptual criteria used for wood evaluation can be primarily based on the tactile, visual and auditory sensory modes, we thus designed the test in four parts. The three first parts of the test were created to evaluate, separately, the respective contributions of the different perceptual modes. The final part of the test was an overall evaluation, aiming to reproduce, as closely as possible, the habits of luthiers in their workshop. Except for the last part, each protocol follows the same outline. First, some attributes are evaluated to establish a sensory profile of the wood blank according to each sense. This part allows us to characterize the product and to learn how the attributes may define a board's quality as excellent or unusable. The blanks were then evaluated with a general quality rating for each sense. Finally, an acceptance test was performed to determine the emotional attachment to the product.

In the first part of the protocol, the resonance woods were evaluated through hearing only. Makers were asked to evaluate several attributes such as "pitch", "sound duration", and "crystallinity". In the second part, the sense of touch was tested. The makers were asked to evaluate the top or back plates by touching the surface of the material only, then by weighing it. Makers had to evaluate the "roughness", "hardness", and "density" of the material. The third part focused on vision. The panel observed the samples without touching them. The selected attributes were, for spruce top plates, "ring width" and "regularity", "latewood percentage", "cutting plan", "colour", "gloss", and "hazelnut growth" (indented rings). Finally, the overall evaluation was conducted by letting makers use all their senses, as they would usually do in their workshop. This overall evaluation included a quality rating, an acceptance test and optionally free verbalisation.

The relative weight of the considered perception senses—used to examine the material's quality—and the attributes favourably perceived by different senses to define a good top plate were determined. The evaluation of the makers was analysed in regard to the physical measurements of the specimen in order to characterize their perception. As the test was time-consuming (ranging from 40 minutes to two hours), the analyses of the psychosensory study on spruce are currently based on seven complete responses only. Therefore, the number of participants is not yet significant.

While observing the evaluation of each wood blank according to the general quality rating for the different perception senses, we observed different kinds of variability interacting with the obtained results. Firstly, the perceived differences between plates differed according to each sense of evaluation: discrimination between different spruce blanks, for instance, was more difficult to access by the auditory rating than through the visual, tactile or overall ratings (Fig.5). This variability could be attributed to two causes: (1) the makers could indeed perceive more differences through the tactile, visual or overall senses than by using their auditory senses only (which means that the auditory perception might have less weight than the tactile or visual perception); (2) the perceived differences could be due to a flaw in conception of the protocol (the makers could have felt more confident during the successive steps of the test and thus given more and more adamant evaluation).

Second, we observed variability between different makers' behaviour. We observed diverse quality rating values according to the makers—some makers always gave lower ratings than others—as well as differences in the distribution behaviour—for example, some makers tend to give wider differences in ratings between the various top plates.

To define a “good top plate”, we first isolated the attributes that are favourably perceived by the makers by looking at the correlation between individual attributes and the general quality rating for each sense. Afterwards, we analysed the perceived attributes in relation to the physical measurements that we had previously conducted on the specimen. The results (Table 3) show that the auditory quality rating of the wood blanks is mainly correlated to attributes that express the damping (“length/duration of sound” and “crystallinity”), which is consistent with results from the literature [23]. At the same time, according to the correlation with the measured wood properties (Fig.6), it also appears that the auditory attribute which the makers perceived most is “pitch”, which is an indication of the resonance frequency or sound wave celerity. For a constant geometry—which is the condition of the material during our test—the higher the “pitch” of the fundamental note, the higher the speed of sound. In short, it is an indicator of the specific modulus of elasticity of the wood. However, on a daily basis, in the real conditions of workshops, the dimensions of the blank wedges for plates are highly varied. Therefore, this parameter (pitch) cannot be taken into account in practice—unlike the damping, which is less linked to geometry. Thus, the behaviour of makers—not taking pitch into account—is adapted to their usual work situation.

Concerning the evaluation of wood through tactile sense, the main attribute to define a “good” wood blank was its density ($R=0.73$ between evaluation of attribute—from “very dense” to “very light”—and the

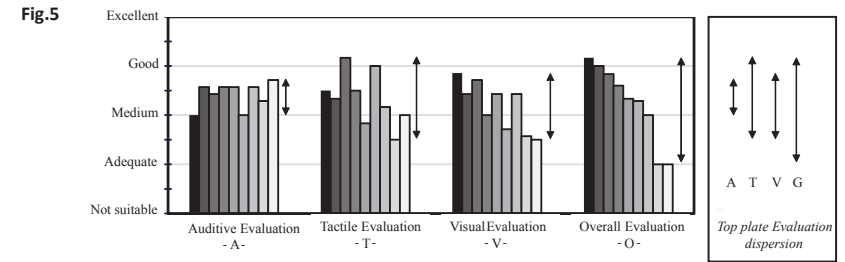


Table 3

Perceived attributes		Correlation to :	
Perceived Pitch	Pitch	-0.04	Auditory rating
Perceived Length	Len.	-0.56	
Perceived Crystallinity	Cry.	0.47	
Perceived Roughness	Rou.	-0.10	Tactile rating
Perceived Hardness	Hard.	-0.30	
Perceived Density	ρ	0.73	
Perceived Ring width	Rw	-0.46	Visual rating
Perceived Regularity	Reg	-0.31	
Perceived Cutting	Cut.	-0.41	
Perceived Latewood %	Lw%	0.27	
Perceived Gloss	Gloss	-0.41	
Perceived Colour	Colour	-0.20	
Perceived Hazelgrowth	Hg.	-0.20	

quality rating for blank plates), which was also well perceived by makers ($R=-0.89$ between evaluation of attribute and measured property). However, during our test, since the geometry of the wood blanks was constant, the density evaluation was not made under the same conditions as those that usually apply for makers. Their rating of density is directly due to an approximation of the perceived mass. Thus it is questionable whether, in real life condition with the blank-plates of varying dimensions, the estimation would have been as strongly correlated to actual measurements as the results that we obtained.

Fig.5 Top plate average ratings and variation range obtained during the four phases of the psychosensory test.

Table 3 Correlations between sensory attributes and their quality rating evaluation. A value in bold indicates a significant correlation according to the Pearson-Bravais table with an α -risk of 0.05.

Fig.6

		Perceived					
		Pitch	Len.	Cry.	Rou.	Hard.	ρ
Optical characteristics measurement	Ring width	-0.57	0.6	0.33	-0.55	-0.43	0.33
	Latewood	0.63	-0.07	-0.06	0.83	0.93	-0.82
	ring width regularity	-0.33	0.79	0.37	-0.25	-0.2	0.11
	a* color parameter	0.06	-0.01	-0.37	0.73	0.74	-0.6
	b* color parameter	0.24	-0.02	-0.2	0.78	0.82	-0.66
	L* color parameter	0.04	-0.14	0.19	-0.66	-0.68	0.61
	Gloss	0.9	-0.1	0.23	0.59	0.44	-0.53
Longitudinal properties measured	Density ρ	0.56	-0.07	-0.12	0.86	0.97	-0.89
	E_L/ρ	0.92	-0.43	0.21	0.43	0.41	-0.49
	$\tan\delta_L$	-0.98	0.33	-0.3	-0.4	-0.38	0.58
	E_L	0.85	-0.34	0.01	0.75	0.81	-0.8
	z_L	0.77	-0.24	-0.02	0.82	0.89	-0.86
	R_L	-0.03	-0.17	0.24	-0.59	-0.78	0.69
	ACE _L	0.68	-0.42	0.32	-0.15	-0.27	0.06
Radial properties measured	E_R/ρ	-0.75	-0.1	-0.5	-0.41	-0.33	0.33
	$\tan\delta_R$	-0.11	0.05	0.13	-0.12	-0.35	0.62
	E_R	-0.09	-0.13	-0.55	0.49	0.64	-0.58
	z_R	0.3	-0.09	-0.34	0.77	0.9	-0.85
	R_R	-0.82	-0.02	-0.23	-0.75	-0.77	0.79
	ACE _R	-0.63	-0.03	-0.3	-0.55	-0.43	0.28
Anisotropic ratios measured	$E_L/\rho / E_R/\rho$	0.91	-0.22	0.37	0.42	0.37	-0.41
	$\tan\delta_R / \tan\delta_L$	0.43	-0.2	0.24	0.07	-0.15	0.3
	E_L/E_R	0.89	-0.26	0.34	0.42	0.39	-0.41
	z_L/z_R	0.87	-0.26	0.35	0.44	0.42	-0.43
	R_L/R_R	0.94	-0.12	0.42	0.44	0.36	-0.44
	ACE _L /ACE _R	0.65	-0.21	0.3	0.19	0.01	0.08

		Perceived						
		Rw	Reg.	Cut.	Lw %	Gloss	Color	Hg
Optical characteristics measurement	Ring width	0.93	0.6	0.59	0.23	0.38	-0.28	0.09
	Latewood	-0.4	-0.1	0.13	-0.58	-0.13	0.58	-0.09
	ring width regularity	0.78	0.47	0.55	-0.43	0.67	0.25	0.23
	a* color parameter	-0.27	-0.01	0.13	-0.64	0.18	0.82	0.51
	b* color parameter	-0.33	-0.14	0.04	-0.68	0.09	0.71	0.34
	L* color parameter	0.11	0.07	-0.09	0.52	-0.34	-0.78	-0.55
	Gloss	-0.55	-0.38	-0.12	0	-0.63	0	-0.02
Longitudinal properties measured	Density ρ	-0.37	-0.05	0.19	-0.55	-0.12	0.65	0.03
	E_L/ρ	-0.67	-0.56	-0.37	0.15	-0.8	-0.25	-0.39
	$\tan\delta_L$	0.59	0.53	0.24	-0.05	0.79	0.16	0.26
	E_L	-0.63	-0.36	-0.11	-0.26	-0.54	0.25	-0.21
	z_L	-0.55	-0.26	0	-0.36	-0.4	0.4	-0.13
	R_L	-0.06	-0.29	-0.47	0.76	-0.35	-0.87	-0.29
	ACE _L	-0.5	-0.58	-0.5	0.49	-0.85	-0.68	-0.37
Radial properties measured	E_R/ρ	0.32	0.43	0.29	0.12	0.17	0.07	0.46
	$\tan\delta_R$	-0.13	-0.21	-0.5	0.33	0.17	-0.46	-0.44
	E_R	-0.07	0.34	0.49	-0.39	-0.02	0.68	0.52
	z_R	-0.25	0.16	0.4	-0.53	-0.1	0.75	0.33
	R_R	0.39	0.27	-0.01	0.38	0.26	-0.35	0.17
	ACE _R	0.43	0.41	0.36	0.09	0.1	0.02	0.45
Anisotropic ratios measured	$E_L/\rho / E_R/\rho$	-0.56	-0.55	-0.39	-0.05	-0.51	-0.17	-0.52
	$\tan\delta_R / \tan\delta_L$	-0.49	-0.51	-0.65	0.31	-0.29	-0.51	-0.57
	E_L/E_R	-0.58	-0.57	-0.43	-0.03	-0.51	-0.19	-0.56
	z_L/z_R	-0.57	-0.56	-0.42	0.02	-0.51	-0.2	-0.56
	R_L/R_R	-0.51	-0.51	-0.31	-0.04	-0.51	-0.14	-0.42
	ACE _L /ACE _R	-0.56	-0.56	-0.6	0.18	-0.39	-0.41	-0.58

Fig.6 Correlations matrix between attributes perceived by makers and material characteristics and properties. A value in a black cell indicates a significant correlation according to the Pearson-Bravais table with an α -risk of 0.05.

Next, the visual quality rating of top plates was mainly based on the perceived “ring width” (attribute also highly correlated to optical/structural measurements), and to the “cutting plane” and “gloss” attributes. The perception of colour and ring width by makers is fairly accurate when compared to the physical measurements. Furthermore, their perception of attributes of latewood percentage and colour gives them indirect information on the longitudinal radiation ratio, while gloss is correlated with both longitudinal specific modulus and damping.

Finally, in Fig.7 we could see the correlations between the physical, mechanical and vibrational properties of wood with the general quality ratings evaluated according to the four modalities of the test (auditory, tactile, visual and overall). As expected, the tactile evaluation of quality rating is significantly correlated to the measured wood density. It is also well related to both longitudinal and radial wood vibrational properties and indexes (such as impedance or radiation ratio) and to optical

characteristics such as latewood percentage and colour. The visual quality rating evaluation shows a significant correlation with Young’s modulus and specific modulus of elasticity in both longitudinal and radial directions and is also well related to damping and characteristic impedance. The overall quality rating evaluation of spruce plates by the makers is significantly correlated with longitudinal radiation ratio, considered to be a good criterion to describe the resonance woods. It appears that the makers’ perception of visual and tactile attributes gives an indirect—but accurate—indication of the wood’s physical and mechanical properties, while the overall evaluation is a reliable indicator of the radiation ratio.

5. Conclusion

The originality of our approach allowed us not only to explore the question of wood selection under different research areas that are complementary but usually compartmentalised, but also to bring qualified discussion combining different points of view. The survey gave information on the criteria used by the luthiers to choose their wood and a more accurate vision of the parameters that are actually relevant for conducting the physical-mechanical and optical characterisation of resonance woods. The combination of sensory perception and survey study allowed us to better understand the mechanism of material selection by instrument-makers. The contrast between sensory perception and opinion led us to address a variety of subjects, such as the question of the intellectualisation of a gesture or disparity between the makers’ opinion and their actual action. Finally, the opinion and perception of the makers and the scientifically determined characteristics of the materials emphasized each other. This particular aspect is a crucial illustration of the benefit, for the future, of a decompartmentalized approach on studying the aspect of wood selection adapted to a given usage.

Fig.7

		Auditory Rating	Tactile Rating	Visual Rating	Overall Rating
Optical characteristics measurement	Ring width	0.52	0.17	0.2	-0.23
	Latewood	0	-0.68	-0.63	-0.52
	ring width regularity	0.18	-0.03	0.23	-0.65
	a* color parameter	-0.33	-0.61	-0.09	-0.58
	b* color parameter	-0.18	-0.65	-0.3	-0.58
	L* color parameter	0.15	0.73	0.13	0.61
Gloss	0.3	-0.38	-0.77	-0.1	
Longitudinal properties measured	Density ρ	0.01	-0.77	-0.61	-0.56
	E_L/ρ	0.28	-0.29	-0.78	0.24
	$\tan\delta_L$	-0.27	0.36	0.74	-0.11
	E_L	0.11	-0.6	-0.77	-0.17
	z_L	0.1	-0.69	-0.75	-0.33
	R_L	0.2	0.67	0.11	0.78
ACE_L	0.23	0.23	-0.37	0.63	
Radial properties measured	E_R/ρ	-0.37	0.27	0.77	0.1
	$\tan\delta_R$	0.11	0.54	-0.08	0.42
	E_R	-0.28	-0.52	0.07	-0.48
	z_R	-0.13	-0.74	-0.33	-0.61
	R_R	-0.25	0.67	0.82	0.43
	ACE_R	-0.3	0.24	0.76	0.06
Anisotropic properties measured	$E_L/\rho / E_R/\rho$	0.27	-0.24	-0.78	0.1
	$\tan\delta_R / \tan\delta_L$	0.16	0.35	-0.41	0.5
	E_L/E_R	0.26	-0.24	-0.78	0.14
	z_L/z_R	0.32	-0.27	-0.82	0.14
	R_L/R_R	0.33	-0.28	-0.81	0.02
	ACE_L/ACE_R	0.18	0.19	-0.55	0.39

Fig.7 Matrix of correlations between quality rating evaluations by makers and the measured material characteristics and properties. A value in a black cell indicates a significant correlation according to the Pearson-Bravais table with a α -risk of 0.05.

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References

- [1] I. Brémaud, "Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity," *J. Acoust. Soc. Am.*, vol. 131, no. 1, pp. 807–818, 2012.
- [2] I. Brémaud and N. Poidevin, "Approches culturelles et mécaniques dans le choix des bois en facture: cas des archets anciens," in *CIM09: Conf. on Interdisciplinary Musicology. Music and Its Instruments*. Paris: Editions Delatour France, 2009.
- [3] I. Brémaud, "Vers une vision 'ethno-bio-mécanique' des bois - La rhéologie du matériau-bois à l'interface entre diversité botanique et usages en lutherie et artisansats," Univ. Montpellier, 2016, p. 149.
- [4] V. Bucur, *Acoustics of Wood*, 2nd ed. Berlin: Springer-Verlag, 2006, p. 393.
- [5] V. Bucur, *Handbook of Materials for String Musical Instruments*. Switzerland: Springer International, 2016, p. 975.
- [6] C. Buksnowitz *et al.*, "Resonance wood [Picea abies (L.) Karst.] – evaluation and prediction of violin makers' quality-grading," *J. Acoust. Soc. Am.*, vol. 121, no. 4, p. 2384–2395, 2007.
- [7] A. Tolbecque, *L'art du luthier*. Niort: author (printer: Th. Mercier), 1903.
- [8] I. Brémaud, "What do we know on 'resonance wood' properties? Selective review and ongoing research," in *Proc. Acoustics 2012, Nantes*.
- [9] C. Carlier, "Une approche décloisonnée des 'bois de résonance' d'épicéa et d'érable : critères de sélection et variabilité du matériau en lutherie du quatuor sous les points de vue artisanaux, mécaniques, acoustiques et sensoriels," Univ. Montpellier, 2016, p. 169.
- [10] A. S. Allen, "'Fatto di Fiemme': Stradivari's violins and the musical trees of the Paneveggio," in L. Auricchio, E. H. Cook, and G. Pacini, Eds., *Invaluable Trees: Cultures of Nature, 1660–1830*. Oxford: Voltaire Foundation, 2012, p. 301–15.
- [11] V. Klein and B. Buob, Eds. *Luthiers de la main à la main*. (n.p.): Actes Sud, 2012, p. 192.
- [12] C. Carlier, I. Brémaud and J. Gril, "Violin making 'tonewood': comparing makers' empirical expertise with wood structural/visual and acoustical properties," in *Proc. Int. Symp. on Musical Acoustics ISMA2014*, Le Mans, 2014.
- [13] C. Carlier, I. Brémaud and J. Gril, "The role of tonewood selection and aging in instrument 'quality' as viewed by violin makers," in *Proc. 3rd Annual COST Action FP1302 WoodMusICK Conf.*, London, 2015, pp. 9–10.
- [14] I. Brémaud, J. Gril and B. Thibaut, "Anisotropy of wood vibrational properties: Dependence on grain angle and review of literature data," *Wood Science and Technology*, vol. 45, p. 735–754, 2011.
- [15] C. Barlow, "Material selection for musical instruments," in *Proc. Institute of Acoustics*, vol. 19, no. 5, p. 69–78, 1997.
- [16] E. Obataya, T. Ono and M. Norimoto, "Vibrational properties of wood along the grain," *J. Materials Science*, vol. 35, p. 2993–3001, 2000.
- [17] D. W. Haines, "The essential mechanical properties of wood prepared for musical instruments," *Catgut Acoust. Soc. J.*, vol. 4, no. 2, p. 20–32, 2000.
- [18] H. Yano, I. Matsuoka and J. Mukudai, "Acoustic properties of wood for violins," *Mokuzai gakkaiishi*, vol. 38, no. 2, p. 122–127, 1992.

Musical instruments are fundamental tools of human expression that reveal and reflect historical, technological, social and cultural aspects of times and people. These three-dimensional, polymeric objects—at times considered artworks, other times technical objects—are the most powerful way to communicate emotions and to connect people and communities with the surrounding world. The participants in WoodMusICK (WOODen MUSical Instrument Conservation and Knowledge) COST Action FP1302 have aimed to combine forces and to foster research on wooden musical instruments in order to preserve, develop and disseminate knowledge on musical instruments in Europe through inter- and transdisciplinary research. This four-year program, supported by COST (European Cooperation in Science and Technology), has involved a multidisciplinary and multi-national research group composed of curators, conservators/restorers, wood, material and mechanical scientists, chemists, acousticians, organologists and instrument makers. The goal of the COST Action was to improve the knowledge and preservation of wooden musical instruments heritage by increasing the interaction and synergy between different disciplines.

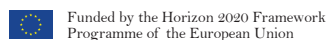


Wooden Musical Instruments — Different Forms of Knowledge



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*Book of End of WoodMusICK
COST Action FP1302*

Edited by MARCO A. PÉREZ and EMANUELE MARCONI



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