COMPARING THE SOUND OF GOLDEN AGE AND MODERN VIOLINS: LONG-TIME-AVERAGE SPECTRA

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Abstract

Recordings of the sound spectra produced by violins made by Antonio Stradivari (15), Giuseppe Guarneri del Gesù (15), and 18 contemporary makers were analyzed and compared. In general, the sound produced by the 30 violins crafted by the two great Italian masters is very strong in the region from about C#$_4$ to G$_4$ (274 to 410 Hz) and significantly stronger in the high-frequency region from F#$_7$ to G$_7$ (2901 to 3073 Hz) and from B$_7$ to G#$_8$ (3868 to 6494 Hz). The particular group of modern violins we analyzed had relatively equal or stronger fundamentals at very low notes below C$_4$ (<260 Hz), in the mid-frequency region A$_4$ to F$_7$ (440 to 2793 Hz), and at very high frequencies (>6.5 kHz). Overall, the sound produced by the violins of Stradivari and Guarneri was darker, less nasal, somewhat stronger in the high-brightness region, and possibly less sharp than was typical of the modern violins.

Most violinmakers and violinists are keenly interested in the similarities and differences in the tonal qualities produced by the finest old and modern instruments. Do modern violins compare to the old master instruments in tone? Are there similarities between the sounds of violins made by the most famous old makers? We seek to answer these questions by analyzing the sound spectra obtained from commercial recordings made by two prominent violin soloists, one playing on representative examples of the greatest of the old Italian violins and the other performing on a selection of fine modern violins made by highly respected contemporary makers.

For the first set of recordings, *The Miracle Makers*, produced by Bein & Fushi, Inc. [1], Elmar Oliveira played an excerpt from the opening of the Sibelius Violin Concerto on fifteen violins made by Antonio Stradivari and fifteen by Giuseppe Guarneri *del Gesù*, which are listed in Table 1. In the second set of recordings, *The Legacy of Cremona*, produced by Dynamic Srl., Italy [2], Ruggiero Ricci played an excerpt from the second-movement cadenza of the Beethoven Violin Concerto on eighteen violins made by well-known contemporary makers, which are listed in Table 2. A booklet with pictures and a short biography of the violin and/or the makers accompanied both sets of recordings. Some of the modern makers are highly profiled and have done well in violinmaking competitions; some also have acted as judges in various competitions.

Table 1. The analyzed old Italian violins
(From *The Miracle Makers* [1])

No.	Maker	Date	Name
1	A. Stradivari	1679	*Hellier*
2	G. Guarneri del Gesù	1742	*Wieniawski*
3	A. Stradivari	1690	*Auer*
4	G. Guarneri del Gesù	1742	*Sloan*
5	A. Stradivari	1692	*Oliveira*
6	G. Guarneri del Gesù	1737	*King Joseph*
7	A. Stradivari	1701	*Dushkin*
8	G. Guarneri del Gesù	1735	*Sennhauser*
9	A. Stradivari	1707	*La Cathédralè*
10	G. Guarneri del Gesù	1720	*Kartman*
11	A. Stradivari	1708	*Ruby*
12	G. Guarneri del Gesù	1737	*Stern, Panette*
13	A. Stradivari	1710	*Vieuxtemps, Hauser*
14	G. Guarneri del Gesù	1740	*Ysaÿe*
15	A. Stradivari	1709	*King Maximilian*
16	G. Guarneri del Gesù	1734	*Le Violon du Diablè*
17	A. Stradivari	1715	*Baron Knoop*
18	G. Guarneri del Gesù	1735	*Plowden*
19	A. Stradivari	1722	*Jupiter*
20	G. Guarneri del Gesù	1744	*Ole Bull*
21	A. Stradivari	1723	*Kiesewetter*
22	G. Guarneri del Gesù	1734	*Haddock*
23	A. Stradivari	1727	*Dupont*
24	G. Guarneri del Gesù	1739	*Kortschak*
25	A. Stradivari	1734	*Willmotte*
26	G. Guarneri del Gesù	1726	*Stretton*
27	A. Stradivari	1736	*Muntz*
28	G. Guarneri del Gesù	1738	*Kemp*
29	Omobono Stradivari	1737	*Rawlings*
30	G. Guarneri del Gesù	1735	*D'Egville*

Table 2. The analyzed modern violins
(From *The Legacy of Cremona* [2])

No.	Maker	Origin and date
1	Gregg Alf	Ann Arbor, MI, USA, 1997
2	Samuel Zygmuntowicz	Brooklyn, New York, USA
3	Peter Greiner	Bonn, Germany
4	Primo Pistoni	Cremona, Italy, 1997
5	William Müller	Croton-on-Hudson, NY, USA
6	John Dilworth	London, UK, 1998
7	Patrick Robin	Angers, France
8	Alberto Giordano	Genoa, Italy, 1999
9	David Bagué i Soler	Barcelona, Spain
10	Roger Hargrave	Meyenburg, Germany
11	Christoph Götting	Michelmersch, Hampshire, UK
12	Luiz Bellini	New York, USA
13	Frédéric-Hugues Chaudière	Montpellier, France
14	Domenico Fantin	Varese, Italy
15	Joseph Curtin	Ann Arbor, MI, USA 1998
16	Roberto Regazzi	Bologna, Italy
17	Giancarlo Guicciardi	S. Damaso di Modena, Italy
18	Renato Scrollavezza	Canneto Parma, Italy

Previous Work

In an earlier paper [3], we analyzed the spectra from the Bein & Fushi recording in ⅓-octave bands. These bands are nearly equivalent to (slightly wider than) the bandwidth of our listening system and are a much-used standard of resolution in commercial acoustics instrumentation. Each ⅓-octave band spans the frequencies of three or four musical halftones. In the present work, we have extended the analysis to higher-frequency resolution in 1/12 octaves, which is equivalent to analyzing a half note per band. Earlier investigators (Bazant, Stepaněk, and Melka) [4] found a high correlation between 1/12-octave band spectra, obtained from a swept sine signal fed to the bridge, and the subjective sound quality of violins.

Method and the Music

Since the musical compositions used for the tonal comparisons on the two CDs were different, we had to find the connection between the time-average spectra from each of the musical pieces. Therefore, we had the same professional violinist (Gunnar Ihlen of the Norwegian National Opera Orchestra) play both the Sibelius and the Beethoven excerpts on five different violins in the same room. The sequence was recorded on a DAT tape for later analysis on a Norsonic 840 unit capable of 1/12-octave band analysis. We also recorded scales on each of the instruments for comparison and made time-average ⅓-octave band analysis using a light Norsonic 118 unit during the session. By subtracting the average spectra from the Beethoven from the Sibelius pieces, it was possible to significantly reduce the effect of the room and the player on the spectra. We refer the interested reader to the Appendix for basic information about the sound meters and filters and our normalization of the audio spectral measurements.

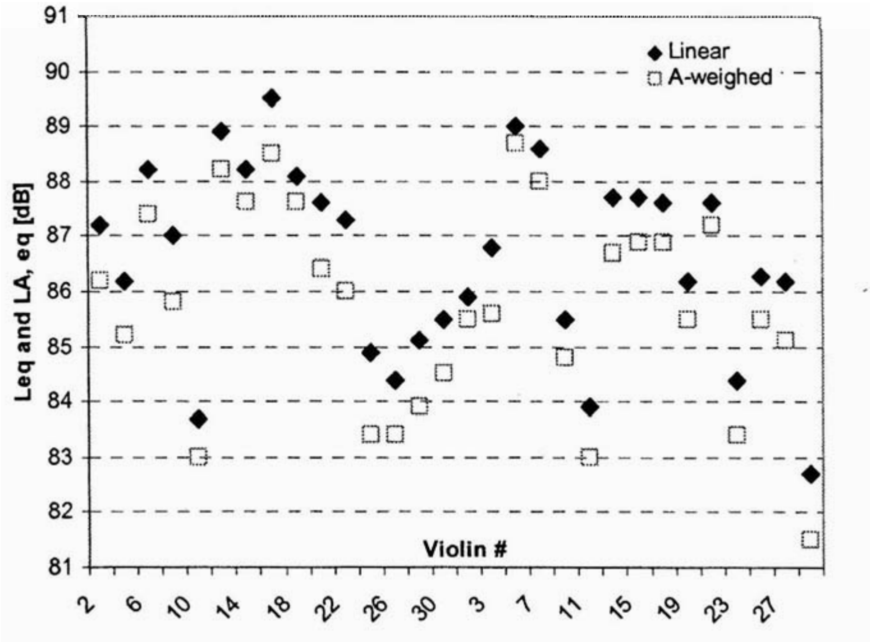
Results

First we compare the summed equivalent sound pressure levels of each played violin, as shown in Fig. 1. The sound pressure levels have been corrected so that the average level over the old and the contemporary violins is equal. We see from Fig. 1a (old Italian violins) and Fig. 1b (modern violins) that the levels varied from ~83 to 91 dB. For the old Italian violins, the difference between the most and least powerful recordings was 6.8 dB; for the modern violins it was 7.5 dB. This level span is quite considerable. We illustrated this difference by playing *four* of the weakest recordings simultaneously to get almost the same sound level as the most powerful of them. Doubling the number of equally strong sources by a factor of two resulted in a 6 dB increase in the total sound level. However, the subjective perception of a 7 dB increase is a little under a doubling of the *perceived* sound level, which may sound less dramatic than the example illustrates.

Some of the variation was related to how similarly the two violinists played the pieces. From studies under controlled conditions by Gabrielsson and Jansson [5], the variance introduced by the violinist playing scales in a reverberant room was less than 1 dB, so we assumed that it would be about the same for our conditions. A 1dB difference in sound level is just about noticeable.

Several studies of vibration levels and sound radiation from a number of violins have shown a natural variation of ~8-10 dB over the frequency bands [6-8]. Müller attributed this variation to differences in the wood quality from bad to very good [7]. We would, however, be surprised if "bad wood" had been used in the construction of any of the fine violins included in this study. Most of the variation should come from the physical instruments, the set up, properties of the wood, plate thicknesses, and maybe other (unknown) factors influencing the sound power from these instruments.

If we count instruments within each 1 dB and scale by dividing each count by the total number of violins in each group, we get a picture of how the variance is distributed. That the old instruments were more evenly distributed in sound level than were the modern is revealed in Fig. 2.



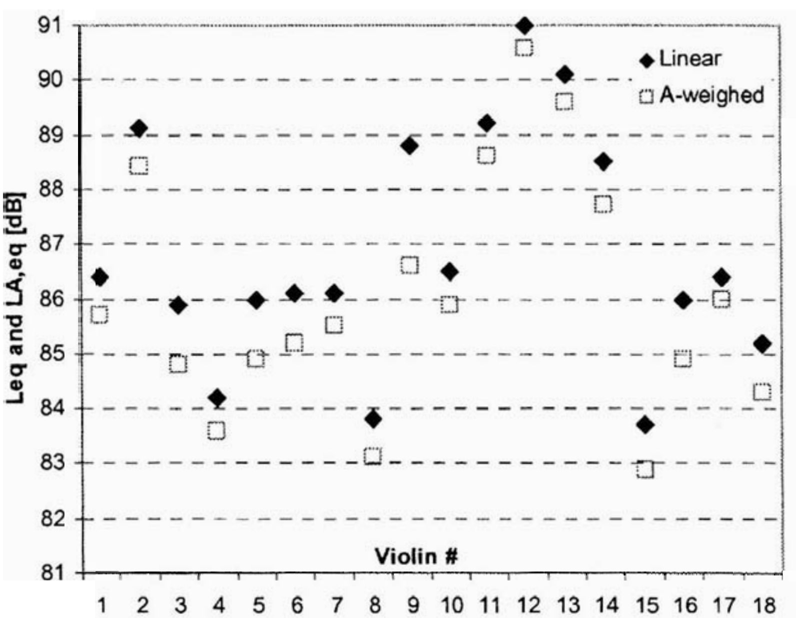
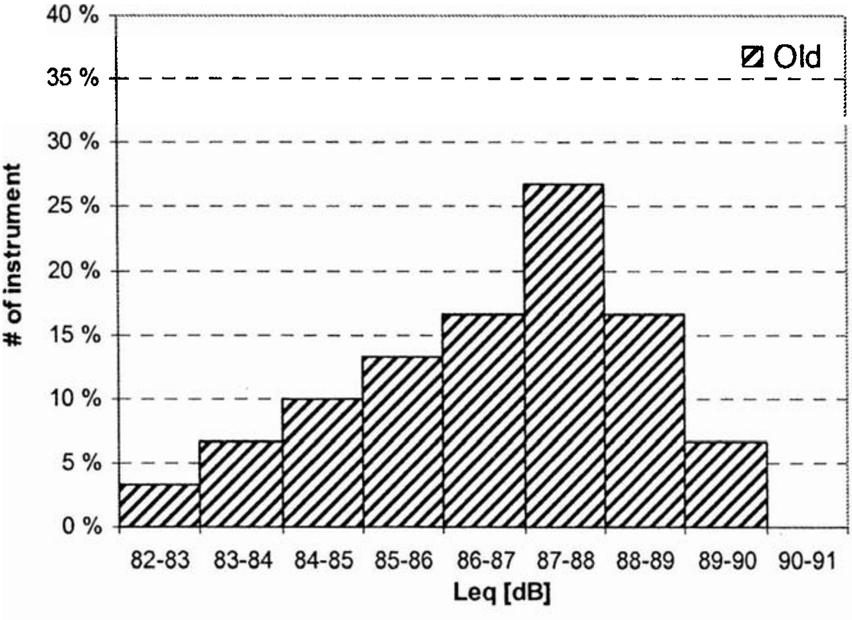


Figure 1. a) Time-average sound pressure levels from the old Italian violins: Guarneri del Gesù violins to the left (even numbers) and Stradivari violins to the right (odd numbers). b) Time-average sound pressure levels from the modern violins (lower graph).



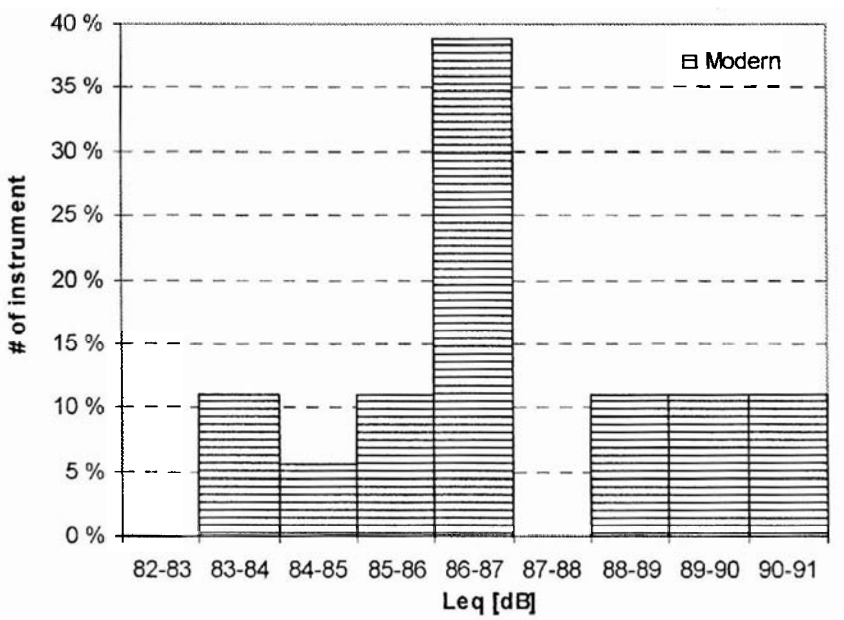


Figure 2. Distribution of sound levels among the 30 old Italian violins and the 18 modern violins.

We would expect a "clock curve," i.e., a normal distribution. Our group of modern violins had relatively more instruments in the "center bar" from 86-87 dB, while there is a rather flat "non-clock" distribution around it. This indicates that the building philosophy and wood may have been more uniform among the "center-bar makers." The more uneven distribution was more expected for the eighteen different modern makers than for the Cremonese makers of the 17th-18th centuries.

When we look closer at the old instruments by dividing them into two groups, we get a "flat clock" among the Strads and two smaller clocks among the Guarneri, as shown in Fig. 3. The number of instruments (fifteen) in each group was, however, a bit small to draw conclusions, e.g., about the seeming two groups among the Guarneri violins. But we see that the curves in Figs. 3 are smoother than for the contemporary violins shown in the right side of Fig. 2. Even if one could be tempted to read out of Fig. 3 that the Guarneri were slightly stronger, their average levels were not significantly different. Both averages were close to 86 dB. A comparison between the average sound levels among the old and the modern violins can't be done as their averages were *adjusted* to be the same. This was our best guess because we had no common reference signal on the recordings. Such reference sound signals are not pleasant sounds to have on a musical recording.

The average sound level of ~86 dB is that typically found near to a violin. At the player's ears the sound may be ~10-15 dB higher, depending on the music and how strongly the player chooses to play. For the musician concerned about his/her ears, it is worth considering using earplugs. A weaker sounding violin while not being on stage will also pose less risk of damage to the ears.

The single number for a measured sound power level by itself does not tell much about the *timbre* of the tone. We see from Fig. 1 that the difference between the linear equivalent level (not corrected pressure level, L_{eq}) and the A-filtered SPL, $L_{A,eq}$, from the violins is typically ~1 dB. It will be larger when there is more bass sound from the instrument, or smaller if there is less bass. For example, we would expect the violin by D. Bagué i Soler to have a rich bass spectrum since the $L_{A,eq}$ and L_{eq} for this violin differ by ~2 dB.

The linear (uncorrected) levels are likely to give a better idea of how loudly the instruments sound under the player's ears. The violins will sound brighter to a listener at a distance than to the player. This is due to our listening systems' lower sensitivity to bass sounds and slightly higher sensitivity to higher frequencies at lower sound levels. More than two single numbers will, of course, better describe the perceived timbre of the sound. We need to look at the detailed spectra to learn something more about the timbre.

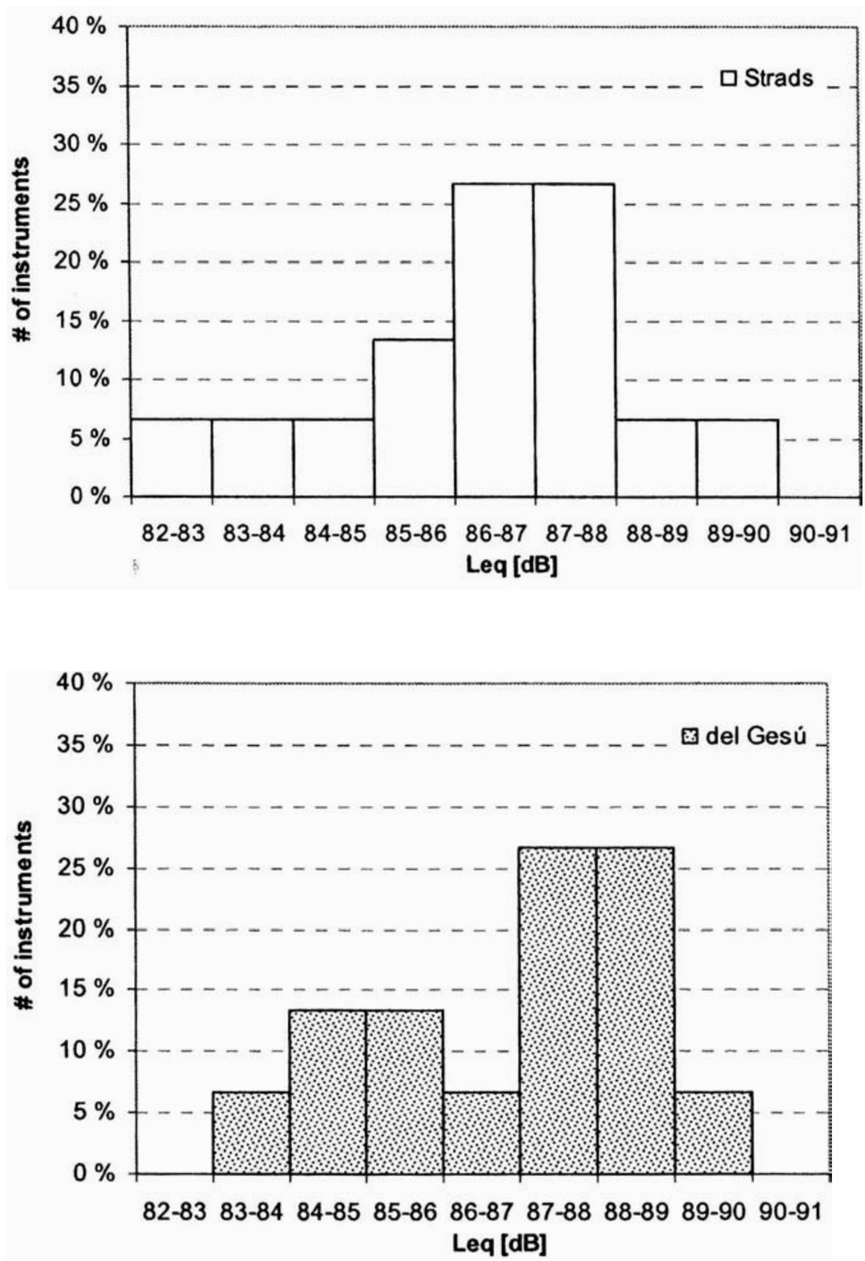


Figure 3. Distributions of sound levels among the 15 Stradivari violins and the 15 Guarneri del Gesù violins.

Comparisons of the Sound Spectra

The main aim here was to compare the modern violins with those of the old Italian masters, but we also show the average curves for the Stradivari and Guarneri *del Gesù* violins for comparison. In Fig. 4 we see that the Strads and the Guarneri have quite similar average spectra. To better see the difference between them, we subtracted one spectrum from the other, as presented in Fig. 5. We have also performed a statistical test (t-test) to determine if the differences we see are significant, "just interesting," or not different. Our definitions were somewhat inspired by Bissinger and Gregorian [9]: 1) *"There is a difference"* = significance levels (p-values) < 5%, 2) *"There may be a difference"* = significance levels between 32 and 5%, and 3) *"There is no difference"* = significance levels < 32%.

We see that the six to seven first-half notes played on the G string, G_3-C_4 (196-260 Hz), have stronger fundamentals for the Strads. The next two half notes, D_4 and $D\#_4$ (290-307 Hz), are stronger for the Guarneri violins, possibly due to their "main air" resonance being somewhat higher. There is also a region from $A\#_4$ to C_5 (460-516 Hz) and the note D_5 (579 Hz) where the Guarneri violins appear to be stronger than the Strads. The tone B_4 is close to the minimum found between the first, B^-, and second "baseball" resonance, B^+, in violins, and the D_5 is slightly higher than the region we normally find the B^+. This might indicate that the B^+ is located slightly higher in frequency (or tone) for the Guarneri than for the average Stradivari violin.

Around $C\#_6$ and D_6 (1090-1155 Hz) the Guarneri violins seem to be stronger, but from F_6 to B_6 (1372-1939 Hz) and C_7-$C\#_7$ (2054-2175 Hz) the Stradivari violins are relatively more powerful. The same seems to be true for the G_7-$G\#_7$ (3073-3255 Hz) and G_8-$G\#_8$ (6131-6494 Hz) half notes that are the overtones.

Correlating Spectra with Averages: Similarities and Differences

We have shown comparisons between two spectra in one figure at a time and observed the similarities and differences. To analyze a large set of data we need a measure of equality. This is also useful for later comparisons of spectra from new or other instruments to the average curves, or for evaluating any individual instrument from this work.

We can compare two violins (or one violin versus the average) by making a graph of the band levels of one violin as x-values and the corresponding band levels for another violin (or the average curve) as y-values. If the spectra of the two are very similar, the points would be *close* to a straight line; if not, they would

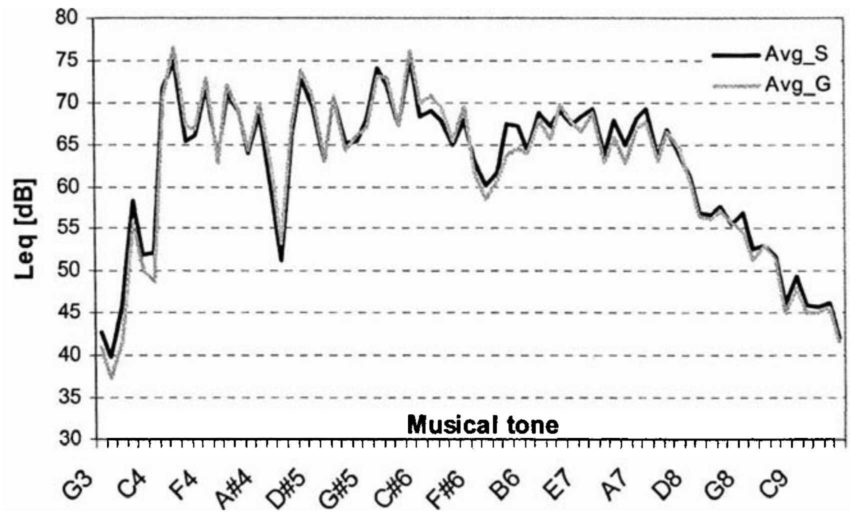


Figure 4. Long-time-average sound spectra of the Sibelius excerpt played on 15 violins made by Stradivari and 15 violins made by Guarneri del Gesù.

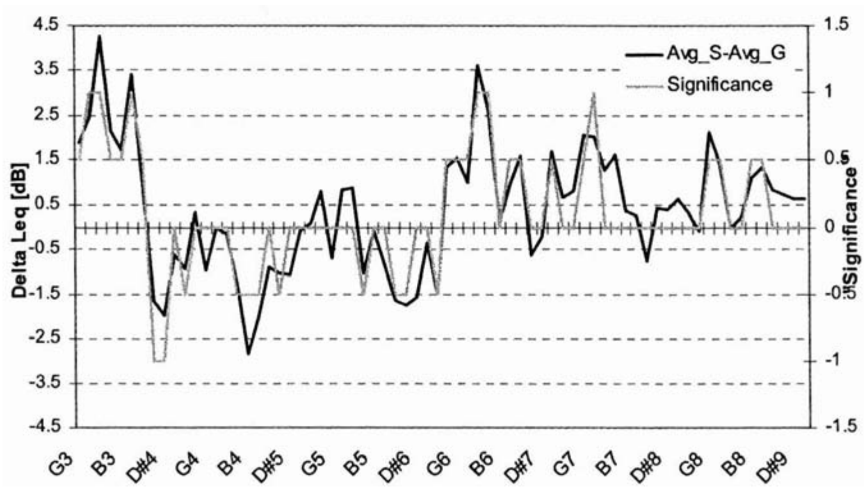


Figure 5. The difference between the average sound spectra from the Stradivari and Guarneri del Gesù violins. The "Significance" numbers ±1 indicate "there is a difference," ±0.5 indicate "there __may__ be a difference," and 0 indicates "no difference."

tend to *spread* across the line. The statistical measure for that spread, called the *correlation coefficient*, gives a precise description of how close the points are to a best-fit straight line. Many spreadsheets have this function implemented. One simply chooses the two spectra to be compared, and the function gives the result as a number between 0 and 1, with 0 indicating "no correlation," and 1 indicating "very high correlation."

By comparing the spectrum for each violin with the average curve and looking at each correlation coefficient, we find that the spectrum for the *La Cathedralé* is closest to the average spectrum of the Strads; the *Oliveira* is least similar. The best method to judge the validity of this result is, of course, to listen to the musical selections. The *Oliveira* sounded brighter than any of the other Strads.

Le Violon de Diable Guarneri *del Gesù* produces a frequency spectrum that is closest to the average Guarneri, while the *Stretton* is least similar. It is interesting to note that the thicknesses of the top plates of these two instruments are similar. However, the thicknesses of their backs differ more than for any of the other Guarneri violins that were both recorded in the Bein & Fushi production [1] and included with plate thicknesses (*Comparisons by correlation of the thickness data for each plate*) in the Biddulph publication, *Giuseppe Guarneri del Gesù* [10]. The *Stretton* has a thinner back and a somewhat different thickness distribution. (See the graduation maps in Schleske's article in *CASJ* May 2002 [11].) This indicates that the back plate thickness must have a significant influence on violin timbre.

Among the Stradivari violins, the spectrum of the *King Maximilian* was closest to the average of the Guarneri *del Gesù* violins tested, while that of the *Kieswetter* Strad was the least similar to the average Guarneri. The *Sennhauser del Gesù* sounded least like the average Strad, while the *Kartman del Gesù* sounded most similar to the average Strad. This might be plausible as it is said that earlier violins of Guarneri *del Gesù* were more similar to those of Stradivari.

This analysis may be understood as an aid when listening to the recordings. Listening indicates that the observations seem reasonably correct, although much information is lost when the spectra are averaged over the entire musical composition. A summary of the results is presented in Table 3.

Table 3. Spectra with highest and lowest correlation coefficients with the average spectrum for the instrument groups: Stradivari, Guarneri, old (Strads & Guarneri), and modern violins.

(Comparisons were made using time-average $^{1}/_{12}$-octave bands.)

Similarity to	Among the Strads		Among the Guarneri		Among the moderns	
	Highest	Lowest	Highest	Lowest	Highest	Lowest
Average Stradivari	*La Cathèdralé*	*Oliveira*	*Kartman*	*Sennhauser*	G. Alf	J. Curtin
Average Guarneri *del Gesù*	*King Maximilian*	*Kieswetter*	*Le Violon du du Diablé*	*Stretton*	G. Alf	J. Curtin
Average old Italian violin (Guar.& Strad)	*La Cathèdralé*	*Oliveira*	*Kartman*	*Sennhauser*	G. Alf	J. Curtin
Average modern violin	*Ruby*	*Rawlings*	*Sloan*	*Sennhauser*	P. Robin	D. Bagúe i Soler and R. Hargrave

Now, how do the modern violins compare with the old Italian violins? We show their average spectra in Fig. 6 where we represent the old ones with their average spectrum. We see that the difference between the old and the modern is somewhat larger than between the two groups of old violins. We see a difference in the low mid-frequency register. To magnify the differences we subtract the two curves from each other and present them in Fig. 7. We have also performed a statistical significance test (t-test) between the old and the modern violin spectra with results shown at the right scale in Fig. 7.

The differences are clearer in Fig. 7 than in Fig. 5. Larger differences may have been introduced by the added variation due to three players and rooms and two musical pieces involved, although we have tried to reduce the differences to a minimum. The players were assumed to have played each piece very similarly. We also assumed that the recordings were made under controlled conditions by top sound producers who were aware of simple acoustical factors. Since we have adjusted the average levels of the old and modern violins to the same level, the comparison was therefore between their relative spectra.

In Fig. 7 we examine four broad frequency regions. The contemporary violins had relatively stronger tone in the mid and low frequencies, while the tone of the older violins was stronger in the low mid-frequency and high-frequency (brilliant) regions. The comparisons are shown in more detail in Tables 4a and b.

From Table 4a we see that basically the fundamentals on the D-string are stronger in the old violins, while the modern have stronger fundamentals very low on the G-string, all over the A-string, and much of the lower E-string. From Table 4b we see that the low brilliance region from 1.5 to 2.5 kHz is dominating in the modern violins, while the old master violins are stronger in the high brilliance region from 3 to 6.5 kHz. The latter observation seems to be in line with the findings by Pickering [12].

At still higher pitch the output power of the modern violins was comparable to or stronger than the old violins, and at very high frequencies the modern violins did seem to be stronger. The frequency region >5 kHz is important for the perception of sharpness, the opposite of darkness [13]. Thus, the old violins sounded considerably stronger in the low mid-frequency region (275-410 Hz), less nasal (650 Hz-1.3 kHz), and somewhat brighter and clearer in the high notes (3-6 kHz).

We may compare the differences between the old and modern violins with the Strad-*del Gesù* differences to see if there might have been a common strategy of using either Stradivari's or Guarneri's methods for building violins. We observe an apparent correlation for the lowest tones from G_3 (196 Hz) to $F\#_4$ (365 Hz) and weakly even to $G\#_4$ (410 Hz). Here we may say that the mod-

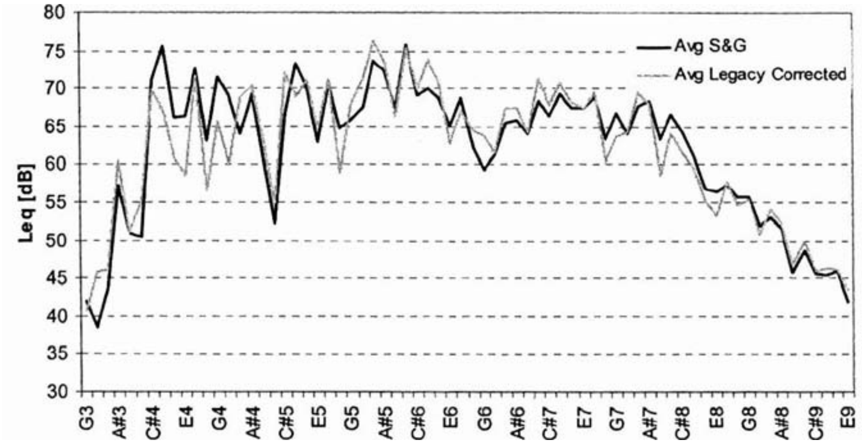


Figure 6. Average sound spectra from the old and the modern violins. The spectrum from the modern violins have been corrected by adding the difference between spectra from the Sibelius and the Beethoven excerpts played in the same room by the same player using five different violins.

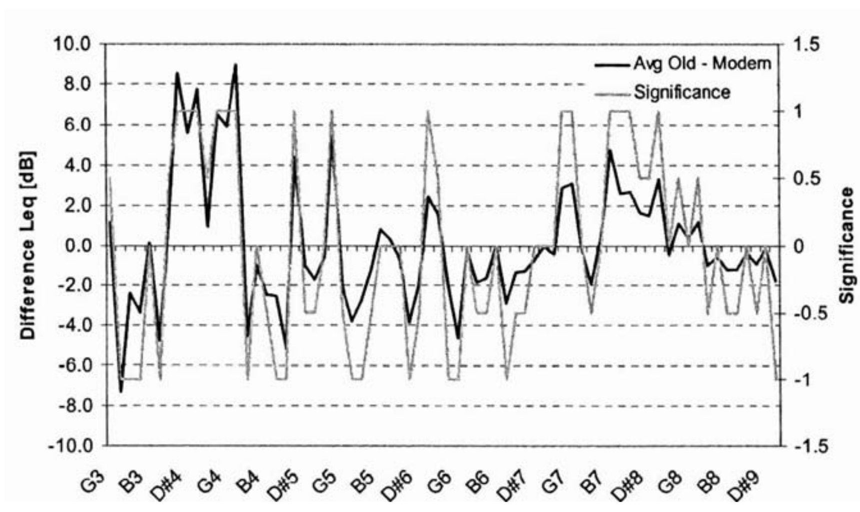


Figure 7. The difference between the average sound spectra of the old and modern violins. The "Significance" numbers ±1 indicates "there is a difference," ±0.5 indicate "there may be a difference," and 0 indicates "no difference."

Table 4a. Comparisons of tone regions with average differences in dB between the average spectra from the old and modern violins.

Tone	$G\#_3$-A_3, C_4	$C\#_4$-$G\#_4$	A_4-$C\#_5$, $D\#_5$-F_5, G_5-$A\#_5$	D_5, $F\#_5$	D_6-$D\#_6$	E_6-F_6
⅟12-oct. band [Hz]	205-230, 259	274-410	434-546, 613-688, 772-917	579, 729	1.15-1.22k	1.3-1.37k
Old–Modern Avg. difference [dB]	-4.4	5.7	-2.5	5.0	-2.9	2.0
Which is stronger?	M	O	M	O	M	O
String fundamental or harmonic	G	(G) & D	(G & D) A & E	A & E	E	E

Table 4b. Comparisons of upper tone regions with average differences in dB between the average spectra from the old and modern violins.
(H = Harmonics, HH = Higher harmonics.)

Tone	$F\#_6$-$A\#_6$ & C_7-D_7	$F\#_7$-G_7	A_7	B_7-E_8	$F\#_8$ & $G\#_8$	A_8-E_9
⅟12 oct. band [Hz]	1.45k-1.83k, 2.1k-2.4k	2.9k-3.1k	3.4k	3.9k-5.2k	5.8k & 6.5k	6.8k-10.2k
Old – Modern Avg. difference [dB]	-2.0	3.0	-1.9	2.7	1.1	-0.9
Which is stronger?	M	O	M	O	O	M
String fundamental or harmonic	E & H	E & H	E & HH	HH	HH	HH

ern violins are more of the "Strad-type," probably with lower main air resonance than the average *del Gesù*. It might also imply that the plates of the modern violins were somewhat less stiff than those of the Guarneri violins. Also, their top plates might have had thinner edges than (at least) the average *del Gesù*.

Other than the very low frequency region, no clear correlations could be seen. (A test gave the correlation coefficient 0.3 with the significant p-value of 3% for the curves in Fig. 8. Comparing the spectra beyond 440 Hz gave no significant correlation.) There was a slightly higher correlation between the spectra of the average Strad and the average modern violin. Of the Guarneri violins, the *Sloan* was similar to the largest number of the modern violins. We are unable to conclude that there was any common preference in spectra for either of the old masters among the contemporary makers.

Such correlation also may be done between each modern violin and their average, and with the average Strad or *del Gesù*. This is an aid when listening to the recordings doing comparisons of the extremes. The modern violins that were most similar to the average were the violins by Robin and Hargrave, while the spectrum of the violin by Bagué i Soler exhibited the least similarity to the average spectrum of the modern violins. The modern instrument having the highest correlation with the average Strad and Guarneri *del Gesù* curves was the violin by Alf. The instrument whose sound spectrum showed the least similarity to those of the old Italian makers, both averages, was the violin by Curtin. If we perform the correlation in ⅓-octave bands (a less precise resolution), the violins by four makers (Alf, Zygmuntowicz, Müller, and Dilworth) had about the same correlation. The least similar to the average old violins in one-third bands was the violin by Chaudière.

To illustrate the similarities and differences, we have plotted the average curves along with the more-or-less similar violin spectra in Figs. 9 to 12. The spectrum of the violin with least similarity to the average of modern violins is presented in Fig. 11.

By comparing each of the old Italian violins with the average curve for the modern violins, we see that the *Sloan* Guarneri *del Gesù* and the *Ruby* Strad are the most similar to this set of modern violins. The similarity is, of course, less than with the average Strad and *del Gesù* curve, but the correlation coefficient is about the same as that between each of the modern and the old average curves. The *Sennhauser* Guarneri and the *Rawlings* Strad produced sound spectra least similar to the average of the modern violins. These correlations are summarized in Table 3.

In Figs. 9 and 12 we still see that the old instruments have a higher response in the upper low-frequency region. Since the Bagué i Soler violin seemed to have substantial power in that

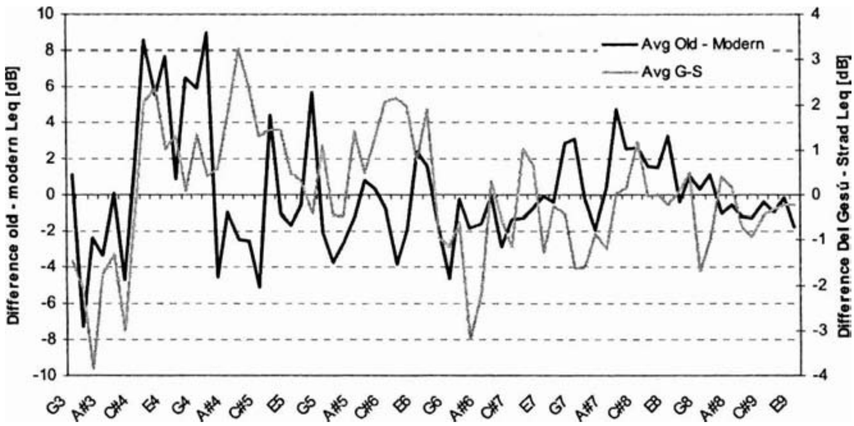


Figure 8. Difference curves: old—modern and del Gesù —Strad. Note the different scales on the two axes to the right and left.

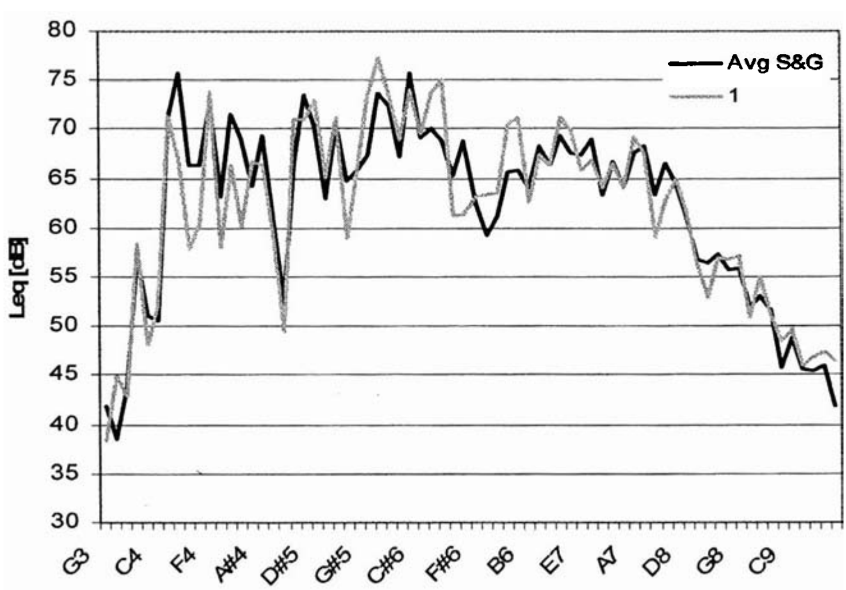


Figure 9. Average of the old Italian violins (by Stradivari and Guarneri del Gesù) and the modern violin with the highest correlation with the old violins.

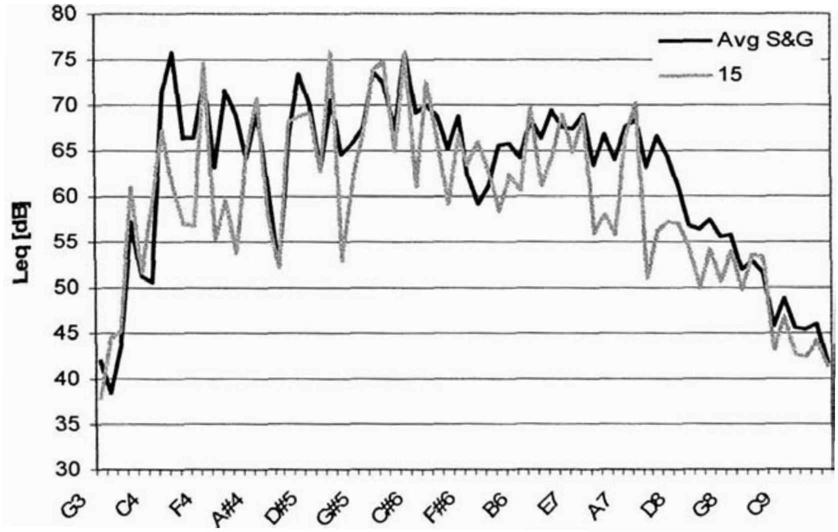


Figure 10. Average of the old Italian violins (by Stradivari and Guarneri del Gesù) and the modern violin with the lowest correlation with the old violins.

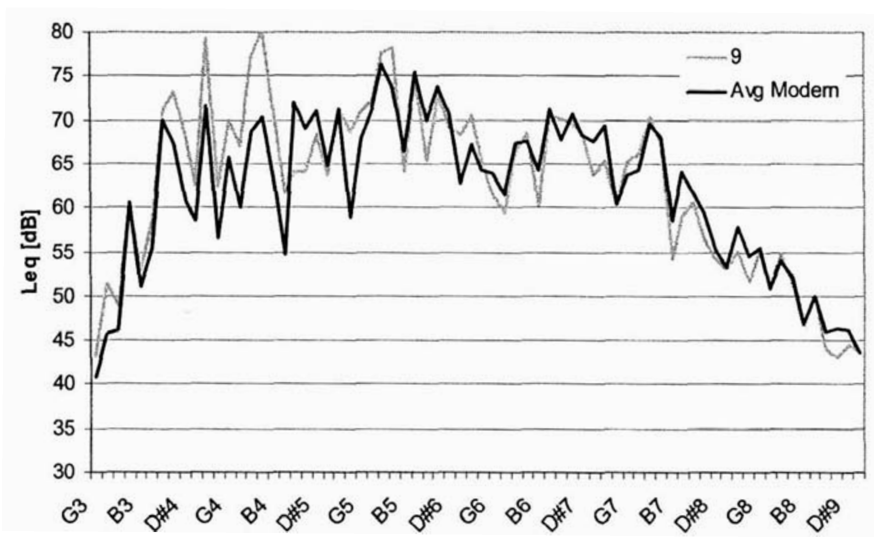


Figure 11. The sound spectrum of the modern violin least similar to the average spectrum of the 18 modern violins had a strong low-frequency response in the octave from C#4 to C#5.

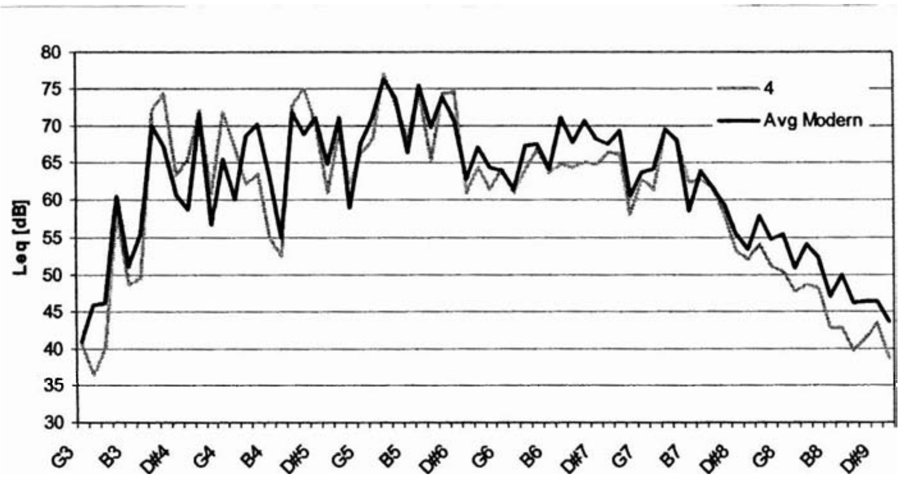


Figure 12. The sound spectrum of the Sloan Guarneri del Gesù had the closest correlation to the average spectrum of the 18 modern violins.

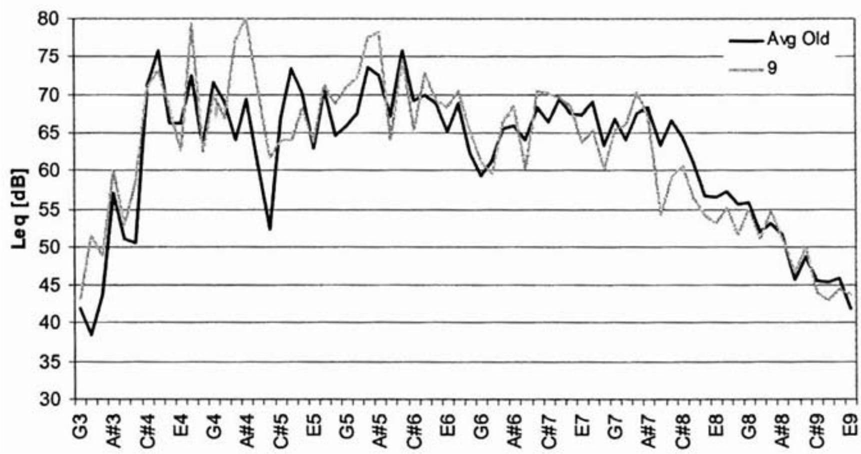


Figure 13. The sound spectrum of the modern violin made by D. Bagué i Soler and the average spectrum of the 30 old Italian violins by Stradivari and Guarneri del Gesù.

region, we plotted its spectrum in Fig. 13 together with the averaged spectrum for the old Italian violins. We see that it had a comparable or even stronger response in this region, especially around A_4-$A\#_4$ (440-460 Hz), which indicates a strong B^- (T_1) resonance. It might be strong here at an expense of a weaker B^+ (C_3) around the $C\#_5$-D_5 (550-580 Hz).

Conclusions (and Questions)

We have shown that there are small, but characteristic, differences between the sound spectra of the average Stradivari and Guarneri *del Gesù* violins. The Strads have stronger low notes on the G-string and higher levels of the higher overtones, making them sound a bit more brilliant. The average Guarneri *del Gesù* is equal or somewhat stronger in the mid-frequency region from the higher notes on the G-string, D_4 to about G_6.

The differences between the average modern violin and the average Strad/Guarneri violin were greater than the differences between violins by these Italian masters, again on average. For the first six half notes, the contemporary violins exhibited Strad-like characteristics, being equal or relatively stronger than the average old master Italian violin. The next eight half notes ($C\#_4$-$G\#_4$) were, however, relatively much weaker. From A_4 and up to about D_7, the contemporary violins were possibly equal or stronger. (Exceptions were D_5, $F\#_5$, E_6, and F_6 where the old were relatively stronger, on average.) The old instruments were stronger in the high-frequency regions $F\#_7$-G_7 and B_7-$G\#_8$. The modern violins seem to have stronger fundamentals on the A- and E-strings, while the old have a particularly strong D- as opposed to the A-string. They also have stronger higher harmonics affecting practically all played notes.

Why do we see and hear these differences? This is certainly not a simple question to answer, but acoustically, plate thicknesses are very important [14-16]. Thickness and the bass bar, most likely, will also influence the radiation efficiency of the violin. Is there a way to predict it in a simple manner? [17, 18] Details of the geometry of the *f*-holes seem to affect high frequency response [16, 19]. Is there something to learn from the present knowledge and methods used in guitar acoustics, such as reported by Richardson [20], Chaigne [21], and their collaborators?

We need to collect more data, not only thickness, but also wood parameters, weights, and tap tones, arching heights, bridge details, details about the position of the sound post (how do we know that a violin is properly set up?), and sound speeds in cross and length directions of the violin plates. (Regarding tap tones, why not collect more than only the fifth mode frequency? We can hear at least six to seven of the plate modes; what we hear we may expect the old master did as well.) All these are parameters that may be registered in most violin shops today. Of course there remains the question of how to perform the data collection in a standardized way to permit valid comparisons.

Other questions concern the players: Have the preferences of modern violinists regarding the timbre of violin tone changed from those of violinists of the past? Do we agree upon what is good timbre? Do psychoacoustic tests on violin recordings measure the quality of the violins being evaluated or the preferences of the particular group of listeners involved? Would the results (if any) apply to violins in general?

Summary

We have presented a simple method of analyzing long-time-average sound spectra from short music pieces obtained from recordings with the same pieces played on a significant number of violins. By simple statistical methods we have found the recordings with the closest similarity to the averages for the Strads, the Guarneri *del Gesù*, and the modern violins. The results may be used as an aid for listening to the tracks with most and least similarities with either group of instruments [1, 2]. The method should be feasible for comparing new instruments to the average spectra obtained from this work by playing the Sibelius or the Beethoven excerpts and analyzing either in $\frac{1}{3}$- or $\frac{1}{12}$-octave band spectra. (Finer resolution may also be used, but the amount of data becomes very large to process.) To reduce the risk for single room resonances at >200 Hz, a room with a reverberation time of ~1 second should have a volume larger than 100 m^3. For a "deader" (living) room with ~0.5-second reverberation time, a room volume ≥50 m^3 should be sufficient.

Finally, the author concedes that correlation of long-time-average spectra is, of course, a simplification. Numbers can't carry the total subtle information connected to music and musical instruments. The author invites the reader to listen to the two comparison CDs [1, 2] and compare your evaluations to what has been noted in this article.

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Appendix: Sound Pressure Level Meters, Filters, and Normalization of Measured Spectra

The sound pressure level (SPL) meters used for these tests were off-the-shelf instruments commonly used for measurements in building-, room-, working health- and environmental acoustics applications. The most usual reading they may give is the time-averaged sound pressure level during the measurement period, the so-called equivalent sound pressure level, $L_{p,eq}$, often written as L_{eq}. This is a single number, and the simplest SPL meters only display such digits for the whole period of measured sound.

Our ears are less sensitive to bass sounds and slightly more sensitive to sounds in the range of 2 to 4 kHz (C_7 – C_8). We may say that our listening system does not have a flat frequency response [22]. And to make things even more complicated, this frequency response changes slightly with the loudness of the sound to which we are listening. At high loudness we hear the bass a little better. (This is the reason why some of us use the "loudness" button on the stereo to boost the bass when we are playing [pop or rock] music at low volume. If we turn the volume up, we may hear that the music played at a higher loudness does not need much of a bass boost).

As an early attempt to simulate the frequency response of our ears, SPL meters were equipped with filters given the names A, B, C, etc. The A filter, in a somewhat simplified manner, was supposed to emulate our ear's frequency response at a sound pressure level, $L_{p,eq}$, of ~55 dB, the B filter for sounds from ~55 to 85 dB and the C filter for $L_{p,eq}$ higher than 85 dB. Only the A and C filters have survived in practical use. In the present paper the A-filtered sound pressure level is denoted as $L_{A,eq}$. The difference between the digits for A- and C-filtered time-averaged sound pressure levels, ($L_{C,eq}$ – $L_{A,eq}$), gives valuable information about the amount of bass the sound may contain, a useful number when we have no ability to see the whole sound spectrum. It is also useful for compression of information into just a single number. For musical sounds from a violin, for example, the C-filtered sound pressure level, $L_{C,eq}$ and the unfiltered level L_{eq} are practically identical. The latter is used in this paper.

The SPL meters also have choices for different speeds of response, technically termed the time constants. This is also an artifact from historical SPL meters where the loudness was displayed by a needle (like most other early measurement equipment). The needle could be reacting "slow" or "fast" to the recorded sound. A slow response made it easier to read off the average sound pressure level by sight. The measurements in these tests were made with a "fast" time constant, which had a reaction time of ~125 milliseconds. This is the most commonly used time constant, e.g., as used in present-day architectural acoustics measurements.

By subtracting the average SPL spectra from the played Beethoven from the played Sibelius piece we substantially reduced the effect of the room and the player on the spectra. The connection between the two musical pieces was found by the following operation for each $\frac{1}{12}$-octave band:

L_{eq} (Sibelius played by Ihlen) – L_{eq} (Beethoven played by Ihlen) +
L_{eq} (Beethoven played by Ricci) » L_{eq} (Sibelius played by Ricci) .