Stradivari violins exhibit formant frequencies resembling vowels produced by females

HWAN-CHING[1] TAI AND DAI-TING CHUNG[2]

Abstract—Over the past two centuries, violins made by Antonio Stradivari (1644-1737) have been more favorably received by concert violinists and instrument collectors than instruments by any other maker. Some suggest that Stradivari's success can be attributed to unique tonal characteristics, generally described as brilliance, and this opinion is still widely expressed by leading violinists today. Others believe that the perceived tonal distinction of Stradivari violins may be attributed to psychological bias instead of physical differences, influenced by historical reputation and market evaluation. Furthermore, modern research has yet to clearly identify acoustic differences between Stradivari violins and other professional quality instruments. Since both violin tones and spoken vowels are perceived through steady-state spectral features, we hypothesized that voice analysis techniques may help elucidate the tonal properties of violins. Using linear predictive coding (LPC), a common speech analysis technique, we examined the recorded scales of four Stradivari violins and ten other professional quality instruments, both old and new. On most violin notes, there are typically four or five resonance peaks (formants) below 5.5 kHz. Generally, professional quality violins exhibit formant frequencies (F1-F4) which are equidistant from the formants of male and female voices. But Stradivari violins tend to produce higher formants which are closer to female voices. Stradivari violins also show greater probabilities to emulate the formants of bright-sounding front vowels spoken by females, a tendency shared by other violins judged by concert violinists as having Strad-like tonal characteristics. Our results suggest that, within the sample group being studied, there are measurable and statistically significant differences between Stradivari violins and other professional quality violins in terms of formant features. Having higher formants or having formants that resemble female vowels may be acoustic correlates of the tonal qualities which concert violinists frequently associate with Stradivari violins.

I. INTRODUCTION

Antonio Stradivari (1644-1737) of Cremona, Italy is the most famous violin maker in human history. Over the past two centuries, more violin virtuosos have preferred to play instruments made by Stradivari than by any other maker, followed closely only by his neighbor Giuseppe Guarneri "*del Gesù*" (DG) (1698-1744) [1-2]. Leading concert violinists and instrument collectors usually suggest that they are attracted by the unique tonal qualities of Stradivari and DG violins, and today a famous specimen by either maker can reach auction prices over $10M USD. Stradivari's tone is often described as "sweet" or "brilliant" by experts familiar with their sound [1, 3]. However, not everyone agrees that Stradivari's unparalleled success is primarily due to acoustic factors. Some people suggest that there is no special acoustic distinction between Stradivari violins (hereafter, Strad violins or Strads) and other high quality violins made by hundreds of master makers throughout history. They also suggest that subjective tonal evaluation can be easily biased by psychological factors such as the historical reputation and the exuberant price of Strad violins [4-5].

Many acoustic and physical studies have been conducted to examine if Stradivari violins produce sound differently. These studies have yet to identify consistent and measurable differences between Stradivari violin and other professional quality violins (for reviews and discussions, see ref. [5-9]). To reconcile the apparent discrepancy between the subjective opinion of leading violinists and the lack of objective, confirmatory evidence, some proposed that Stradivari's uniqueness may originate from "hard-to-define" acoustic properties beyond our analytical capacity, which are only apparent to our ear-brain system but not to our measuring equipment [10]. However, clear evidence is also lacking that players or listeners can readily distinguish between Stradivari violins and other master instruments when played side-by-side. For instance, in a recent blind test, a panel of violinists failed to make such distinctions [11].

[1] Hwan-Ching Tai. Department of Chemistry, National Taiwan University, Taipei, Taiwan.
[2] Dai-Ting Chung, Chi Mei Museum, Tainan, Taiwan.

Manuscript received April, 2012.

In this study, we investigated the tonal properties of violins by analyzing their resonance peaks (formants) during actual playing. Generally speaking, the tone quality (or timbre) of a musical note is a set of properties that help distinguish different types of sound production, independent of pitch and loudness. The tone quality of violins is most clearly perceived by listeners in the sustained part of a note, suggesting a strong association with steady-state spectral cues instead of transient ones [5-6]. The analogy in human speech perception would be that vowels are determined by steady-state cues, while consonants are determined by transient cues [12]. The most important spectral features of vowel sounds are the resonance frequencies (formants) of the vocal tract. Listeners rely on formant frequencies to determine both vowel identity and speaker gender. The steady-state spectra of violins also display characteristic formants similar to those of human voices [13-14]. Therefore, we investigated whether formant analysis techniques commonly employed in voice research may be useful for studying violin tonal quality.

Through formant analysis based on the linear predictive coding (LPC) algorithm [15-17], we found statistically significant differences between Strad violins and other professional quality violins in terms of formant properties. LPC analysis revealed that Strad violins generally produce higher formants. The first four formants of Stradivari violins coincide rather closely with those of female voices. Other violins generally exhibit formant frequencies centrally located between those of male and female voices. Moreover, Strad violins show greater tendencies to emulate the formants of bright sounding front vowels spoken by females. Our data imply that there may be a physical difference that underlies the perceived tonal distinction of Stradivari violins, and that there may be a correlation between higher formant frequencies and the brilliant qualities of Stradivari violins often described by concert violinists.

II. Experiment

A. Background considerations about tone analysis

The steady-state spectra of both the violin and human speech can be explained by a source-filter model (Fig. 1A) [18-20]. In both, the vibrating source (the string or the vocal cord) produces a harmonic series that decreases in amplitude with rising frequency. The filter (the violin body or the vocal tract) then attenuates certain frequency bands, generating a pattern of peaks and valleys called the spectral envelope. The tone quality of the violin note and the identity of the spoken vowel are primarily determined by the spectral envelope shape, which in turn is largely controlled by the frequency response function of the filter [5, 18, 21]. These resonance peaks in the spectral envelope are called formants (F1, F2, F3, F4, and so on).

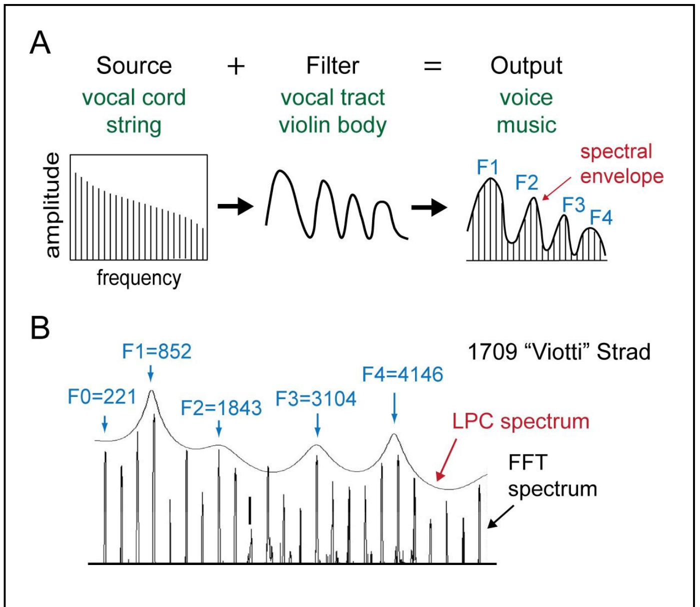

Figure 1. (A) A source-filter model for the human voice and the violin. The vibrating source produces a harmonic series (multiples of F0 in frequency), the amplitudes of which are modulated by filter resonance. Resonance peaks in the output spectral envelope are called formants (F1-F4). **(B)** An example of the fast Fourier transform (FFT) and LPC spectra of a violin note, and its formant frequencies calculated by LPC.

The first four formants of the human voice convey important information about speaker gender, vowel identity, and vowel quality [12, 22]. Formants are basically resonance frequencies of the vocal tract at which standing waves are formed. Therefore, the shorter vocal tracts of females compared to males lead to shorter standing waves and higher formant frequencies [23]. In speech, listeners use both fundamental frequencies (F0) and formants to determine speaker gender [22], but during singing F0 is matched to the musical pitch and hence formants become the primary gender cue [24-25]. On the other hand, vowel identity is primarily differentiated by F1 and F2 values, which in turn are determined by different tongue positions and mouth shapes [26].

Intriguingly, it has been observed that people can consciously match different violin notes with different vowels when instructed to do so, and the chosen vowel may vary from one semitone to the next on the same violin [14]. The perceptual capacity to match violin notes to vowels has also been demonstrated in children [27]. Therefore, the brain may have the capacity to associate the spectral features of violin notes with vowel formants. This also implies that vowel formants and violin formants may be analyzed similarly. One of the most commonly used computational approaches for vowel formant analysis is LPC [16, 22], and recently some researchers have also applied LPC to analyze string instruments [28-29]. In this study, we applied LPC formant analysis to study the spectral envelope of violins, focusing on steady-state regions of long, sustained notes without vibrato.

B. Violin recording

We recorded the scales of 14 violins, including four Strads (Table 1), during a one-day session at the recital hall of Chi Mei Museum (Tainan, Taiwan). Except for the Altavilla and the Nagyvary, all violins were generously loaned by the Chi Mei Museum. The instruments were set up by D.T.C. and tuned to A4 ≈ 441 Hz. A Zoom Q3 HD digital recorder (Tokyo, Japan), equipped with two small cardioid condenser microphones in X-Y configuration, was placed 180 cm above the stage floor to make uncompressed 24 bit/48 kHz stereo recordings. Chu-Hsuan Feng, a professional violinist who graduated from the Paris Conservatory, used a French bow by Joseph Henry to play the C major scale (G3-C7) on each violin, once at a distance of 60 cm from the microphone (measured from the bridge), and once at 120 cm. Each note in the scale was played twice consecutively with down bows (1.5-2.0 s) at *forte* loudness without vibrato. The violinist was informed about the maker before recording each instrument, and was asked to maintain a consistent bowing style while playing different violins.

	Maker	Year	Name	Average value of all notes						
				F1 (Hz)	F2	F3	F4	ETL (cm)	*Dm*	*Df*
Group 1 "Strad"	Antonio Stradivari	1707	Dushkin	562	1557	2795	3818	16.13	0.122	0.098
	Antonio Stradivari	1709	Viotti-Marie Hall	533	1648	2748	4042	16.02	0.152	0.079
	Antonio Stradivari	1713	Wirth	512	1701	2822	3888	15.94	0.124	0.104
	Antonio Stradivari	1722	Elman-Joachim	580	1731	2803	3809	15.61	0.144	0.098
	Group 1 average			***547***	***1659***	***2792***	***3889***	***15.92***	***0.135***	***0.095***
Group 2 "Strad-like"	Giuseppe Guarneri "*del Gesù*"	1733	Lafont-Siskovsky	511	1562	2604	3713	16.83	0.111	0.097
	Giuseppe Guarneri "*del Gesù*"	1744	Ole Bull	532	1638	2718	3798	16.53	0.138	0.112
	Ansaldo Poggi	1974		564	1734	2729	3859	15.83	0.140	0.114
	Group 2 average			***535***	***1645***	***2684***	***3790***	***16.40***	***0.130***	***0.108***
Group 3 "Old"	Gasparo da Salò	1560		543	1515	2528	3739	16.95	0.109	0.102
	Andrea Amati	1570	Ross	446	1598	2689	3705	17.13	0.102	0.110
	Nicolò Amati	1624		493	1481	2725	3910	17.13	0.136	0.123
	Giuseppe Guarneri "*filius* Andrea"	1706	Paganini	484	1581	2842	3696	16.85	0.138	0.128
	Group 3 average			***491***	***1544***	***2696***	***3763***	***17.02***	***0.121***	***0.116***
Group 4 "Modern"	Jean-Baptiste Vuillaume	1860		508	1588	2544	3704	16.82	0.088	0.110
	Armando Altavilla	1922		477	1757	2535	3848	16.58	0.089	0.132
	Joseph Nagyvary & Guang-Yue Chen	2006		504	1493	2516	3680	17.25	0.114	0.108
	Group 4 average			***497***	***1613***	***2532***	***3744***	***16.88***	***0.097***	***0.117***
	Average of 14 violins			518	1613	2685	3801	16.49	0.122	0.108

Table 1. Recording and analysis of 14 professional-quality violins. Calculations of formants (F1-F4), equivalent tube length (ETL), and distances to male and female vowels (*Dm* and *Df*) are explained in the main text.

C. Pre-categorization of violins

As the curator of the Chi Mei collection of over 800 master violins, D.T.C. has interacted with many concert violinists who have borrowed and played the instruments being studied. To see if subjective evaluations by musicians may correlate with objective, measurable acoustic attributes, we separated the non-Strad violins into three categories before the recording and analysis. The categorization criterion was simple: if a violin had been considered by many concert violinists as having Strad-like tonal characteristics, it belonged to Group 2 [Strad-like]. Violins considered to lack Strad-like tonal characteristics were further classified by age: those over 300 years old belonged to Group 3 [old], and those made after 1850 belonged to Group 4 [modern].

Concert violinists often express the opinion that the tonal character of top-tier Stradivari violins consists of two major factors: a generally aged sound and a unique quality often described as brilliance. While most violinists agree that well-made and well-preserved violins would generally acquire an aged sound over two or three centuries of playing, there is much debate about the nature and the existence of the brilliance factor. Furthermore, neither factor has been successfully characterized and explained through modern acoustic research.

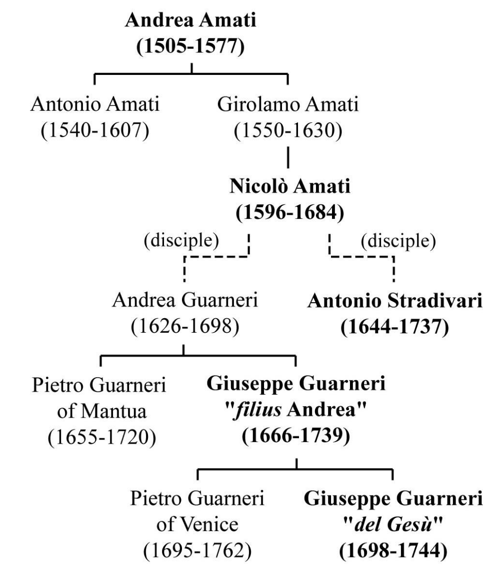

Figure 2. Genealogy of famous violin-making families in Cremona, Italy. The names in bold are included in this study.

The four Strads included in this study are generally considered by concert violinists as fine examples of well-preserved Strads with brilliant and beautiful tones, and, as a matter of fact, all of them were formerly owned by world-class soloists. Also, according to many concert violinists, it is very rare to encounter other violins which possess Strad-like characteristics, and those rare exceptions are mostly made by DG, the famed neighbor of Stradivari. Group 2 [Strad-like] violins in this study included two historically renowned DG instruments and a 1974 modern Italian violin by Ansaldo Poggi, which, according to some concert violinists, apparently lacked the aged sound of antique instruments but exhibited exemplary tonal brilliance reminiscent of the Strads.

Group 3 [old] consisted of four antique Italian violins that predated the Strads studied. These included the works of Giuseppe Guarneri "*filius* Andrea" (DG's father), Nicolò Amati (the teacher of Stradivari and DG's grandfather), and two founding pioneers of Italian violin making, Andrea Amati of Cremona and Gasparo da Salò of Brescia (see Fig. 2). Although the tonal qualities of Group 3 violins are also highly appreciated by concert violinists, they are not considered to possess the brilliant characteristics of Strads. Group 4 [modern] included a violin made by J. B. Vuillaume, one of the most famous copyists of Stradivari in the 19th century, and two professional quality violins made in the 20th and 21st century.

D. Choosing an LPC method for violins

In speech research, LPC algorithms have been refined over decades to produce reliable formant identification. These optimizations are based on known features of human speech and tested against speech transcripts annotated by listeners. To our knowledge, no study has yet optimized LPC algorithms for violins. Hence, we took three popular speech analysis programs (Praat, SFS and WaveSurfer) and empirically tested their performances on violin recordings, trying different combinations of built-in analysis parameters.

After testing these three software programs, we found that Praat's LPC analysis (based on Burg's maximum entropy method [30]) with the appropriate parameters produced the most consistent results with violin spectra. We judged the quality of LPC prediction by the stability of formants (least shift within the same note) and by visually comparing LPC formant predictions to FFT spectra. It turned out that default LPC parameters for analyzing female voices in Praat (5 formants under 5.5 kHz) also worked best for violin analysis. Because the length of recorded violin notes was >1500 ms, the analysis window was increased from 25 ms for speech to 150 ms for violins for better frequency accuracy. Pre-emphasis was not applied to violins because they have considerably less high-frequency roll-off than human voices. When analyzed using these empirically determined LPC parameters, each violin note typically showed four or five stable formants (Fig. 1B). In this study, we focused on the analysis of the first four formants.

E . Formant analysis by LPC

LPC analysis was performed using Praat Software (version 5.2.28) [15], which implemented the maximum entropy spectra proposed by Burg [30]. We used the following LPC parameters: maximum formant frequency=5500 Hz, maximum formants=5, time window=0.15 s, dynamic range=70 dB, and no pre-emphasis. The analysis was performed on the stereo recording, without separating left and right channels. Each pair of repeated notes was analyzed using Praat's spectrogram display, with formants labeled by colored dots to help visualization. We tried to identify a region within each note pair with at least four formants that showed the greatest stability. The LPC analysis window was then placed at the center of that steady-state region. Generally, a violin note showed four to five formants, although some regions might exhibit only three formants or unstable, shifting formants. Hence, it was advantageous to play each pitch twice to ensure that a region with four or five steady-state formants was available for analysis. For each violin, 14 LPC spectra were extracted (G3, A3, B3, C4, E4, F4, and G4, each recorded at two distances, omitting D4 due to technical errors during recording). Publicly available anechoic recordings [31] of a violin and a Bb trumpet (G3-G4 at *ff* and *mf* loudness) were downloaded from the University of Iowa website and analyzed similarly. Statistical analyses (Mann-Whitney test, Kruskal-Wallis test, and Fisher's exact test) were performed with GraphPad Prism 5 software (La Jolla, CA).

III. Results and Discussion

A. Strad violins exhibit higher formants

Empirically, we observed that Praat's LPC formant analysis is best suited for analyzing the spectral envelope when F0 is smaller than 400 Hz. If F0 is too high, the harmonic partials are too far apart to reflect the peaks and valleys in the spectral envelope, and formants are much harder to define. For this same reason, when people sing a note above 400 Hz, vowel intelligibility starts to decrease drastically with rising pitch as formants become harder to recognize, and also because F0 starts to exceed F1 [32]. Thus, from a psychoacoustic perspective, it is also less meaningful to consider formants when F0 is too high and the harmonic gap is too large.

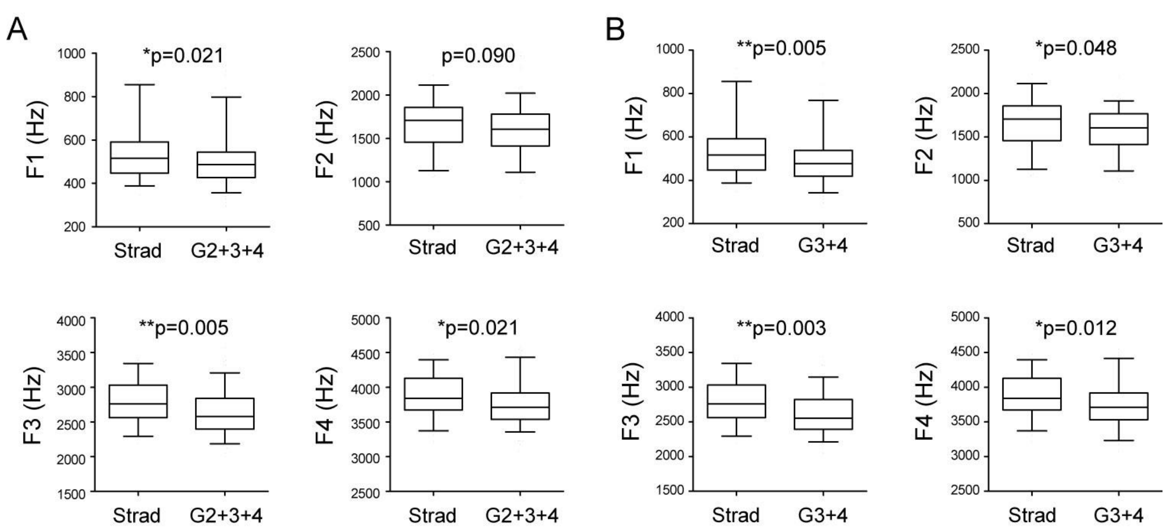

Figure 3. Stradivari violins have higher formant frequencies compared to other violins. Four Stradivari violins were compared against 10 other violins (Group 2+3+4) in **(A)** and against only Group 3+4 violins in **(B)**. Statistical comparisons were made by Mann-Whitney test (*p<0.05, **p<0.01). The box represents 25%, median, and 75% values, and the whiskers represent 5% and 95% values.

In this study, we applied LPC formant analysis to the lowest octave (G3-G4, F0=196-392 Hz) of the recorded violin scale. Even at the lowest notes, a violin can still produce clear formants above 4 kHz, which is an octave above the highest playable note (for example, see Fig. 1B). Hence, the spectral envelope of the lowest notes still provides much information about the full-range response of the violin. The radiativity profile of the violin drops rather quickly above 4 kHz [33], although the useful output range may extend to 7-8 kHz.

Typically, we found that each violin note exhibited 4-5 formants below 5.5 kHz, and we focused on understanding the first four formants. The average F1-F4 values of the 14 recorded violins are listed in Table 1. Comparing Strad violins against all other violins (Group 2+3+4), we found that Strads tended to produce higher formant frequencies (Fig. 3A). The differences in F1, F3, and F4 were statistically significant ($p<0.05$), and there was also a trend toward significance in F2 ($p=0.090$). When we excluded Group 2 violins from the comparison, which were specially selected for their Strad-like tonal characteristics, the statistical difference between Strads and other violins (Group 3+4, old and modern) became even more pronounced. In this case, Strads exhibited significantly higher frequencies in all four formants (Fig. 3B).

Comparing each group separately, we observed that Strad violins had the highest averages in F1 through F4, and that Group 2 [Strad-like] had the second highest averages in F1, F2, and F4 (Table 1). By one-way ANOVA (Fig. 4), there were significant differences in F1 ($p=0.016$) and F3 ($p=0.0006$) between the groups, and a trend toward significant differences in F4 ($p=0.074$). Strads had higher F1 than Group 3 [old] ($p<0.05$), and higher F4 than Group 4 [modern] ($p<0.001$). Altogether, our data suggest that the four Stradivari violins examined generally produced higher formant frequencies, especially in F1 and F3.

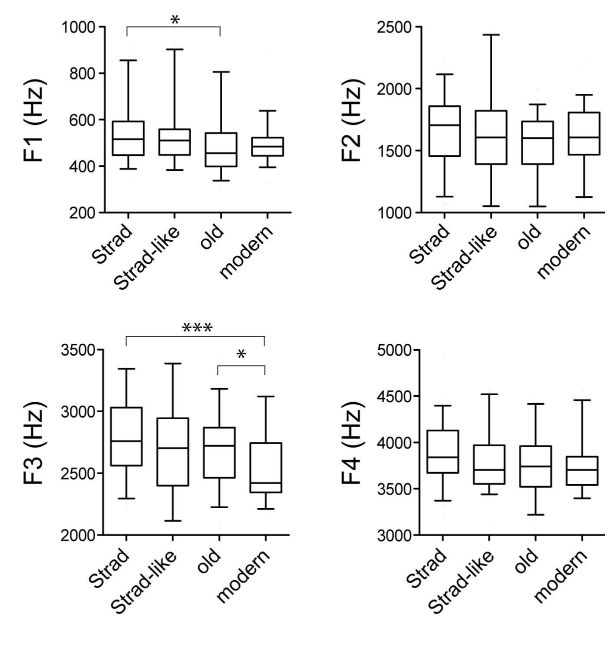

Figure 4. Formant frequencies of different violin groups. Statistical comparisons were made by Kruskal-Wallis one-way ANOVA, followed by Dunnett's post test to compare all pairs (*$p<0.05$, **$p<0.01$, ***$p<0.001$). The box represents 25%, median, and 75% values, and whiskers represent 5% and 95% values.

B. Violins and vowels share several formant features

Recent studies by Bissinger have shown that, in addition to the cavity (air) mode around 280 Hz, the radiativity profile of the violin is dominated by three corpus modes: the corpus bending mode around 500 Hz, the BH (originally called "bridge-hill") mode around 2.4 kHz, and the bridge-filter mode around 3.5 kHz [33]. These vibration modes were measured with an impact hammer striking the bridge [34], which was rather different from our study in which violins were naturally bowed and recorded in a concert hall. Nevertheless, we still expected to see LPC-estimated formants to closely relate to the major corpus modes measured by impact response.

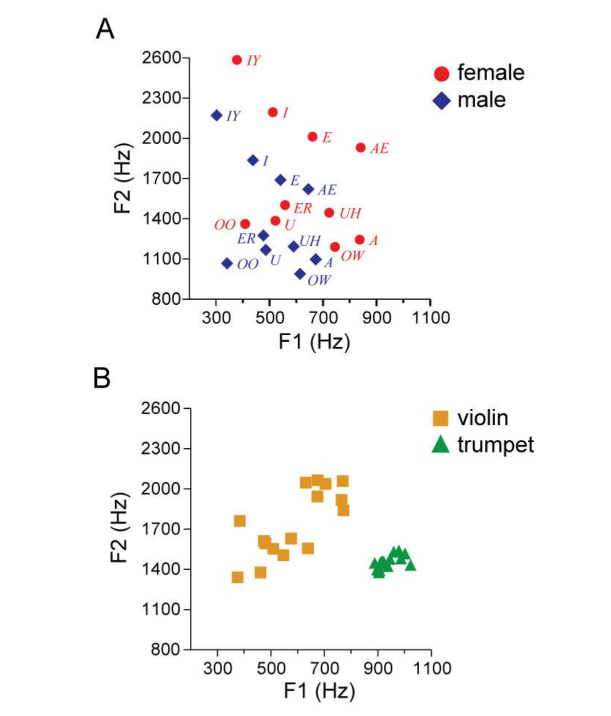

Figure 5. (A) 10 basic female and male vowels shown in the F1-F2 formant space, based on published measurements [21]. **(B)** Violin notes (G3-G4, 196-392 Hz) have greater F1 and F2 variations than corresponding trumpet notes. Recordings taken from a publicly available instrument sound library [30].

The F1-F4 averages of our 14 violins were 518, 1613, 2685, and 3801 Hz, respectively (Table 1), and therefore F1, F3, and F4 appeared closely related to the dominant corpus modes mentioned above. The major resonance frequencies are slightly higher in our recordings than Bissinger's force hammer measurements, which may be due to complex experimental factors such as the act of bowing, the violin hold, microphone placement, and room acoustics. This also validates that our LPC parameters were chosen properly. We can tentatively assign F1 to the corpus bending mode ($B1^-$ and $B1^+$), F3 to the BH mode, and F4 to the bridge-filter mode. Upon closer examination, there is also a minor peak in the violin corpus mobility curve around 1625 Hz [33], which may potentially relate to violin F2.

Interestingly, the major resonance modes of the violin corpus (0.5, 2.4, 3.5 kHz) follow a 1:5:7 ratio starting at 0.5 kHz, while male voice formants (511, 1411, 2370, 3428 Hz, Table 2) also follow a 1:3:5:7 ratio starting at 0.5 kHz. This may explain why LPC analysis commonly used in voice research can be successfully applied to violin spectra. The average F1-F4 of our 14 violins (518, 1613, 2685, 3801 Hz) fell squarely between the formants of the male voice (511, 1411, 2370, 3428 Hz) and the formants of the female voice (619, 1686, 2842, 4053 Hz). Whether by coincidence or by design, the strongest resonance modes of the violin above 400 Hz can emulate the formants of the human vocal tract.

Moreover, violins and voices both exhibit large variations in formant frequencies, especially in F1 and F2. In human speech, variations in F1 and F2 are caused by variable tongue positions and mouth shapes associated with different vowels, and each vowel occupies a distinct region in the F1-F2 plane (Fig. 5A). Unlike the voice organ, there are no moving parts in the violin, and therefore F1 and F2 variability are possibly due to the existence of relatively sharp resonance peaks, which would only be excited strongly if a harmonic partial is very close to their resonance frequencies. To rule out the possibility that F1 and F2 variability is a computational artifact due to applying LPC to our violin recordings, we also tested digital recordings from other sources. Every violin we have analyzed consistently displayed large variations in F1 and F2 on successive notes, while some other instruments such as the trumpet displayed very stable F1 and F2 (Fig. 5B). The much larger F1 and F2 variance of the violin compared to the trumpet ($p<0.0001$ by F-test) are apparently related to the inherent properties of the instrument, not computational artifacts.

Interestingly, the formant frequencies of violin notes show no correlations with pitch (F0), which is again analogous to human voice. Raising the pitch in speech or singing has little effect on formant frequencies, except in some highly trained singing styles or when the musical pitch (F0) approaches or exceeds F1 in normal speech [25, 35]. The fact that both violin notes and vowels show large F1 and F2 variations in similar frequency ranges may explain why people frequently hear different corresponding vowels in adjacent semitones played on the same violin [14].

Vowel	IY	I	E	AE	A	OW	U	OO	UH	ER	Avg
Example	beet	bit	bet	bat	Bob	bought	book	boot	but	Bert	
IPA	i	ɪ	ɛ	æ	ɑ	ɔ	ʊ	u	ʌ	ɝ	
Backness	front	front	front	front	back	back	back	back	central	central	
Height	close	near-close	open-mid	near-open	near-open	open-mid	near-close	close	open-mid	open-mid	
Male											
F0 (Hz)	131	130	124	122	120	119	125	129	120	121	124
F1	302	438	541	645	673	614	486	341	590	477	511
F2	2172	1837	1690	1621	1097	990	1168	1067	1194	1276	1411
F3	2851	2482	2456	2357	2457	2465	2307	2219	2401	1707	2370
F4	3572	3533	3511	3463	3463	3408	3359	3342	3423	3201	3428
ETL (cm)	18.07	17.01	16.45	16.22	17.80	18.79	19.09	21.70	17.92	20.56	18.36
Female											
F0 (Hz)	231	227	219	215	213	216	220	222	215	217	220
F1	378	512	661	841	837	745	522	409	723	558	619
F2	2586	2196	2013	1932	1245	1190	1386	1361	1445	1503	1686
F3	3286	2995	2955	2981	2945	2853	2791	2729	2862	2024	2842
F4	4127	4265	4219	4146	3957	3922	3976	3976	4052	3888	4053
ETL (cm)	15.10	14.25	13.66	13.13	15.20	15.91	16.41	17.72	14.91	17.33	15.36

Table 2. Formant data of 10 basic vowels in General American English spoken by males and females. Fundamental (F0) and formant (F1-F4) frequencies are compiled from published data in ref. [21]. Average formant values and equivalent tube lengths (ETL) were calculated in this study. IPA: international phonetic alphabet.

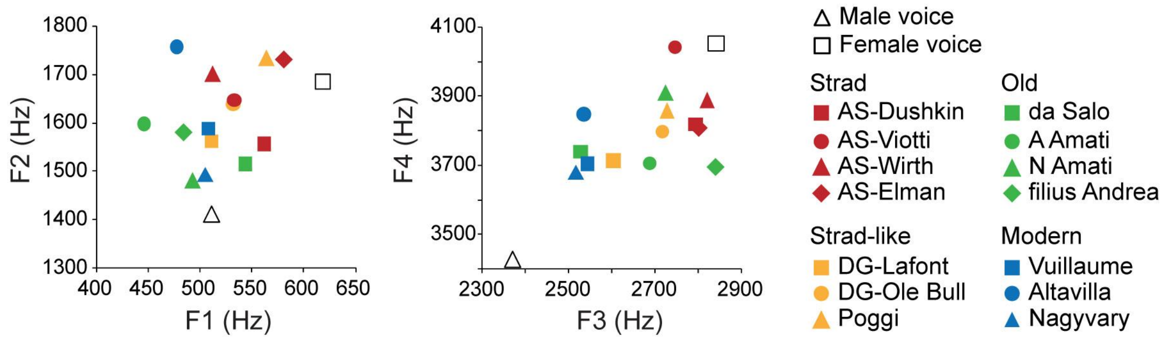

Figure 6. Mean formant values of individual violins plotted in the F1-F2 plane and the F3-F4 plane, compared with male and female means. Stradivari violins (red) tend to be clustered near female means.

C .Strad violins exhibit formants similar to the female voice

Since professional quality violins generally have formant frequencies similar to those of human vowels, and since people can often match violin notes to different vowels, it seems likely that the proximity of a violin note to a vowel or a voice type in the formant space may affect its perception. When we compared the average formants of individual violins to those of female and male voices, we noticed that all four Stradivari violins displayed a proximity to the female voice both in the F1-F2 plane and the F3-F4 plane (Fig. 6). The only other violin to show a comparable tendency was the 1974 Poggi violin, which was pre-selected into Group 2 for its supposed tonal resemblance to Strad violins.

Because voice formants arise from standing waves in a tube with an open end (the vocal tract), they are in fact not independent variables but jointly affected by vocal tract length [23]. A simple estimation of vocal tract length from formant frequencies is given by this formula (c is the speed of sound at 344 m/s, ETL is equivalent tube length):

$$ETL = \left(\frac{c}{4F_1} + \frac{3c}{4F_2} + \frac{5c}{4F_3} + \frac{7c}{4F_4}\right) \div 4\ , \qquad (1)$$

This equates to 15.36 cm for females and 18.36 cm for males (average of 10 vowels, Table 2). While the actual vocal tract is not a straight tube and appears slightly shorter than ETL estimates [36], it has been shown that relative ETL differences are excellent predictors in voice gender differentiation [37]. Thus, it is very likely that voice formants are not just perceived as independent and continuous variables in our brain, but also as conjoined attributes that fall into different gender-vowel categories. Since good quality violins also display vowel-like formants, it seems reasonable to apply ETL calculations to violins as a method to jointly analyze all four formants.

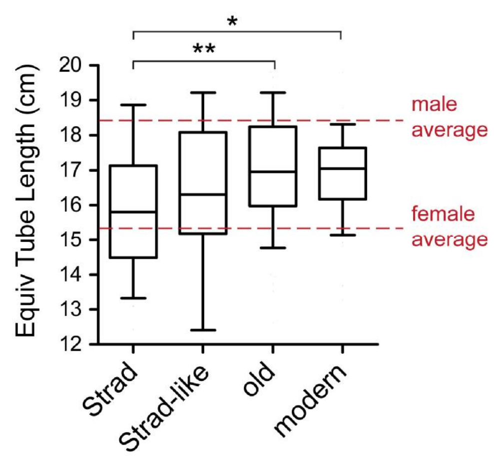

Figure 7. Stradivari violins have lower ETL values than old (Group 3) and modern (Group 4) violins. Red lines represent average male and female ETL values. Statistical significance was determined by Kruskal-Wallis one-way ANOVA, followed by Dunnett's post test to compare all pairs (*p<0.05, **p<0.01). The box represents 25%, median, and 75% values, and whiskers represent 5% and 95% values.

Compared to analyzing each formant individually, the differences between Strads and other violin groups became even more pronounced in ETL analysis (Fig. 7). By one-way ANOVA, the difference between groups was highly significant ($p=0.0043$). The Strads had the lowest mean ETL, followed by Group 2 [Strad-like]. By Dunnett's post-test, we found that the average ETL of Strads (15.92±0.22 cm, mean±SEM) was significantly smaller than those of Group 3 [old] (17.02±0.22 cm, $p<0.01$) and Group 4 [modern] (16.88±0.21 cm, $p<0.05$). The Strad average was also much closer to the female vowel average (15.36 cm) than the male vowel average (18.36 cm). Since instruments in Group 3 are older than the Strads tested, the higher formants and lower ETL of the latter cannot be simply be attributed to aging. In fact, the Poggi violin from 1974 has the second lowest ETL despite its young age, suggesting that it is possible to produce a modern instrument with very high formants.

D. Strad violins emulate the formants of female front vowels

Since there is considerable overlap between male and female vowels in the four-dimensional formant space, we decided to determine the mapping relationship between individual notes and individual vowels by measuring normalized Euclidean distances. First, we tried to determine the distance, called *Dm*, of each violin note to its closest male vowel in the 4D formant space, which is given by this formula:

$$Dm = \sqrt{\left[\left(\frac{F_1}{F_{1m}}-1\right)^2+\left(\frac{F_2}{F_{2m}}-1\right)^2+\left(\frac{F_3}{F_{3m}}-1\right)^2+\left(\frac{F_4}{F_{4m}}-1\right)^2\right]/4} \qquad (2)$$

Computationally, we tested the F_{1m}-F_{4m} values of all ten male vowels in Table 2 to see which vowel produced the smallest distance and called that distance *Dm*. Similarly, we also calculated the distance to the closest female vowel and called it *Df*, and hence each note has a *Dm* value and a *Df* value. Among the four groups, Strad violins exhibited the highest mean *Dm* and the lowest mean *Df*, followed by Group 2 [Strad-like] (Table 1). By one-way ANOVA, the difference between groups was significant for *Dm* ($p=0.0151$, Fig 8A), and highly significant for *Df* ($p=0.0007$, Fig. 8B). *Df* was significantly higher for Strads versus Group 3 [old] ($p<0.01$) and Group 4 [modern] ($p<0.01$). *Dm* was also higher for Strads versus Group 4 [modern] ($p<0.05$). When we plotted average *Df* vs. *Dm* for each individual violin in Fig. 8C, we noticed that Strads and Strad-like violins were located in the lower right region of the graph, characterized by more feminine and less masculine vowel characters.

While calculating *Dm* and *Df*, we also identified the closet vowel to each note in the 4D formant space (considering both male and female vowels together). Then we noticed that there is a much higher probability for Strad and Strad-like violins to project closely to female front vowels (Table 3). Front vowels (including [I], [E], [AE], and [IY]) are vocalized by placing the tongue forward, which raises F2-F4. Because of their higher formants, female front vowels are the brightest sounding vowel group. Although different languages may have somewhat different vowels, basic categorizations such as front vs. back vowels are universal in all languages because they are determined by tongue and mouth movements.

The vowels most frequently emulated by Strad violins are female front vowels [I], [E], and [AE] (41%), followed by female back vowels [OO] and [U] (20%). By contrast, about 36% of Strad notes mapped to the ten male vowels combined. Overall, the probability to map to a female front vowel was higher for Strads vs. Group 3 [old] ($p<0.01$, Fisher's exact test) and for Strads vs. Group 4 [modern] ($p<0.01$). It was also higher for Group 2 vs. 3 ($p<0.01$) and for Group 2 vs. 4 ($p<0.05$). Taken together, the tendency of a violin to project notes that map closely to female vowels (smaller *Df* and larger *Dm*), especially the female front vowels, seem to correlate well with their perceived tonal brilliance.

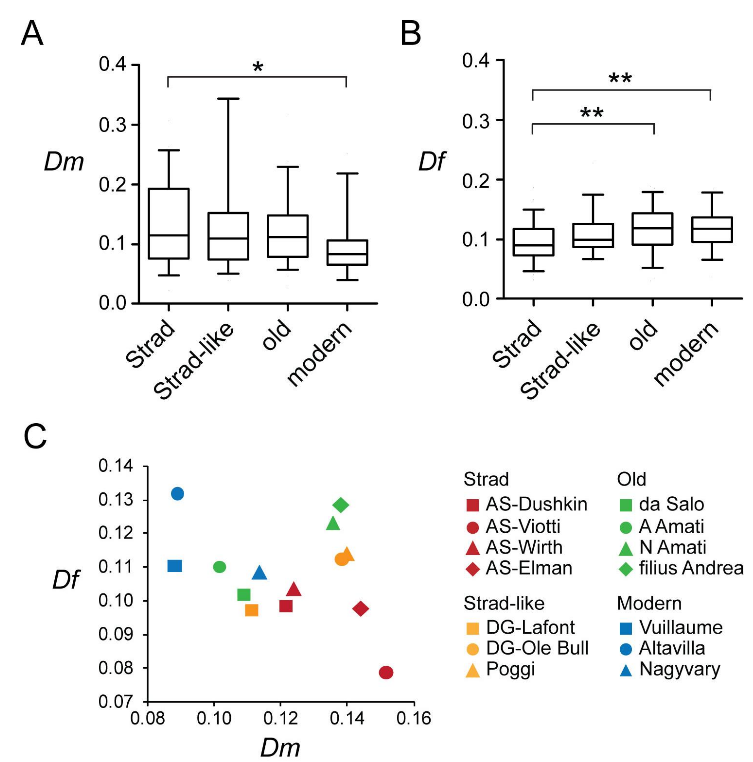

Figure 8. Stradivari violins are characterized by larger distances to male vowels (*Dm)* and smaller distances to female vowels (*Df)*, shown in **(A)** and **(B)**, respectively. The box represents 25%, median, and 75% values, and the whiskers represent 5% and 95% values (Kruskal-Wallis one-way ANOVA, followed by Dunnett's post test to compare all pairs, *p<0.05, **p<0.01). In **(C)**, mean *Dm* vs. mean *Df* is plotted for 14 violins. Stradivari (red) and Strad-like violins (orange) tend to cluster in the lower right region.

E. Strad and DG violins project to unique regions in the formant space

For over 200 years, the majority of violin virtuosos have preferred to play either Stradivari or DG instruments. We therefore investigated if these violins could produce unique sounds inaccessible by other violins. By plotting all recorded notes from the 14 violins in three formant planes (F1-F2, F2-F3, and F3-F4), we searched for regions preferentially occupied by Strad and DG instruments. There turned out to be several such "hot zones" in the formant planes examined (Fig. 9). Over 75% of the notes in these projection zones belonged to the four Strads and two DGs, with each instrument contributing at least 8% (the top three were all Strads). The Poggi also contributed to 7% of the notes and, by contrast, the four violins in Group 3 [old] contributed just 16%. Strikingly, only 1% of the notes in these zones belonged to Group 4 [modern] violins. Upon closer examination, these zones were characterized by higher F2-F4 values, and corresponded closely to female front vowels [I], [E], [AE], and [IY]. This supports our earlier observation that Strad and Strad-like violins are distinguishable by their tendencies to emulate female front vowels, which happen to be the brightest vowel group due to higher formant frequencies.

Violins	Female front vowels	Other vowels
Group 1	23 (41%)	33 (59%)
Group 2	16 (38%)	26 (62%)
Group 3	8 (14%)	48 (86%)
Group 4	5 (12%)	37 (88%)

Table 3. The number of notes in each violin group that map to different vowel categories in the 4D formant space.

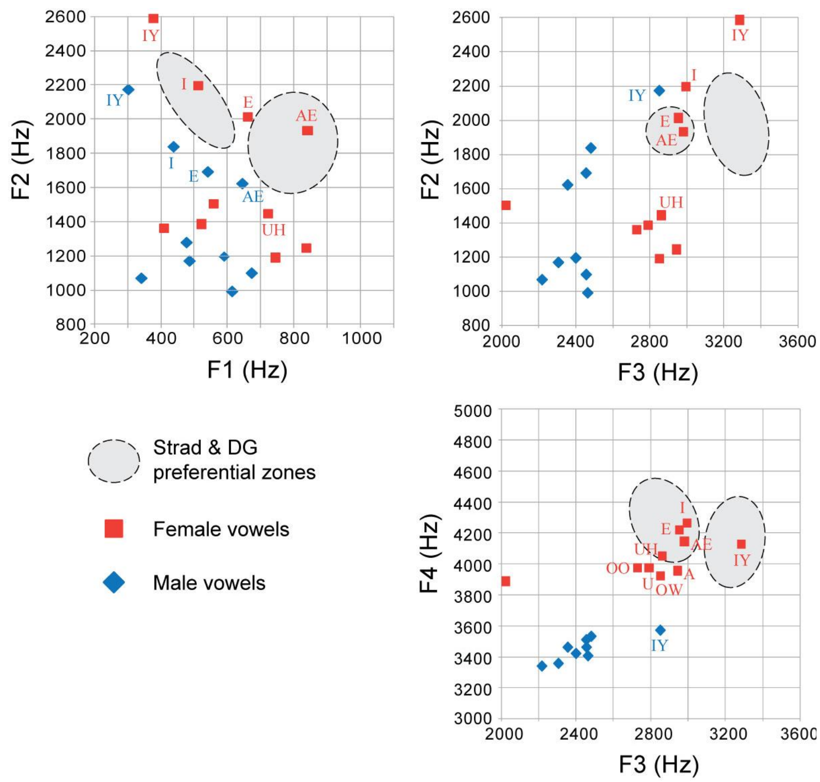

Figure 9. Preferential projection zones of Strad and DG violins in vowel formant planes. Grey ellipsoids represent regions predominantly occupied by notes from Strad and DG violins.

F. Possible correlations with perceived tonal quality

The conventional approach to studying the resonance properties of violins is to measure the response curve by averaging many notes or by physically exciting the instrument without the player. However, this is not how we actually listen to violins. We do not perceive violin tone through its long-time average or the hammer response, but through the harmonic partials of individual notes during very short time intervals. In this study we demonstrated the feasibility of analyzing violin resonance through the LPC spectra of individual notes recorded during normal playing. Our approach can examine the natural sound of the violin without the use of special equipment, just studio microphones. Compared to deriving one response curve per instrument, our method provides much greater statistical power by considering each note individually.

In this study, we pre-categorized the violins according to age as well as tone qualities subjectively described by concert violinists. After recording and analysis, we found that formant features (F1-F4, ETL, *Dm*, and *Df*) appeared to correlate better with perceived tonal brilliance than with age. The only potential age-related difference was observed in F3, where old violins seemed to display higher values (Fig. 4). But it is unclear if this is a coincidence or if it can be generalized to a larger set of instruments.

In human voice perception, higher formants can lead to increased brightness. Voices with higher formants (women and children) are brighter than voices with lower formants (men); vowels with higher formants like front vowels also sound brighter than back vowels [38-39]. Since good quality violins display vowel-like formants, and since people can hear vowel-like characters in violin notes [14, 27], it is plausible that higher violin formants would also lead to perceived brightness. Our data suggest that having higher formants may be an acoustic correlate of what concert violinists perceive as Strad-like tone qualities, but it will require further psychoacoustic experiments to determine if there is an underlying causal relationship.

G. Comparison with previous studies

Another potential explanation for the brilliant tone of Strad violins is that they simply produce more high frequency energy than other violins, which can be measured from the response curve of the instrument. Unfortunately, in this study we did not have sufficient recording samples to derive frequency response curves from long-time average spectra. Nevertheless, comprehensive studies by Dünnwald have already demonstrated that Strads do not have greater output above 4.2 kHz [40-41]. Dünnwald also thought that the favorable tone of old Cremonese violins may be associated with increased output in the mid-range (1300-4200 Hz) [41], while Meinel thought it was favorable to have stronger responses around 2-3 kHz [42]. In a recent study, Anders Buen measured the response curves of 15 Stradivari and 18 modern violins [43]. Based on the curves he published, we made our own calculations to find that Strad violins exhibited stronger resonance around 3073 Hz compared to modern instruments. Studies in electronic violins also suggested that increasing the output in a broad band centered around 3 kHz improved tone quality [44].

Some researchers suggest that having stronger output around 2.5-3 kHz on a violin may impart an advantage that is related to a phenomenon called "singer's formant" [6, 8, 44]. It has been shown that classically trained singers have the ability to merge F3 and F4 (and perhaps even F5) to create a new formant that is stronger and higher than the original F3. Because human hearing is most sensitive around 3-4 kHz, developing singer's formant helps the audience hear the opera singer above the orchestra and the chorus [25, 45]. Similarly, having increased output around 2.5-3 kHz may also contribute to better projection on the soloist's violin (more easily heard above orchestral violins). Among opera singers, there is an interesting correlation between voice type and the center frequency of singer's formant. The more brilliant the voice type, the higher the singer's formant—around 2.5 kHz for bass and baritones, 2.8 kHz for tenors, and 3 kHz for altos and sopranos [46].

In this study, we found F1 and F3 to be most significantly different between Stradivari and other violins. F3 may be related to the BH mode of the bridge-body vibration, and also to singer's formant. If we apply the concept of singer's formant, then Strad violins (F3=2792±43 Hz, mean±SEM) would be comparable to a tenor, and Group 4 [modern] (F3=2532±43 Hz) would be comparable to a baritone. It appears to correlate with the general opinion of concert violinists that Strad violins sound more brilliant and project better, and it may also imply that Stradivari violins produce higher BH mode resonances during actual playing.

On the other hand, F1 appears to be related to the corpus bending modes $B1^-$ (~475 Hz) and $B1^+$ (~541 Hz) [47]. The higher F1 of Strads (547±17 Hz, mean±SEM) compared to Group 3+4 (494±12 Hz) may either reflect a frequency shift in these modes, or a change in the relative amplitude of these two modes. Schleske has observed that $B1^+$ can differ significantly between different violins, and considers it the most important mode in controlling tonal color. Based on his observations, if $B1^+$ is below 510 Hz, it may lead to a soft, dark sound; above 550 Hz, it may lead to a bright sound, possibly harshness [48]. If F1 represents $B1^+$ mode during actual playing, then our data appears to be consistent with Schleske's general observation, which implies that higher F1 may also contribute to brighter tone color.

Generally speaking, the vibration modes of violins can only be measured in laboratory settings using mechanical excitation, such as hitting the bridge with a force hammer. When the violin is held by a violinist in actual playing, it is difficult to make exact physical measurements. We do not yet understand if vibration modes driven by hammer excitation can accurately reflect actual violin sound during natural playing. The string, the bow, the hold, and bowing technique will influence violin vibration and add a lot of variability. There is currently little understanding of what physical differences may contribute to the higher formants produced by Stradivari violins under natural playing conditions.

IV. Conclusion

In this study, we found that the LPC algorithm can be successfully applied to analyze the spectral envelope of violin notes to identify broad resonance peaks, or formants. Analyzing the scale recordings of 14 professional quality violins, we found that violin formants display several notable similarities to human voice formants: 1) violins and voices typically display four or five steady-state formants below 5.5 kHz; 2) the first four violin formants have similar frequencies as the first four voice formants; 3) violins and voices exhibit similarly large formant variations, especially in F1 and F2. There is much formant variability between different notes on the same violin, as well as between different violins. In human voices, there is also much formant variability due to vocal tract differences (generally shorter in women than men) and the vocalization of different vowels.

These similarities may help explain why people can often hear vowel-like qualities in violin notes and are able to match different violin notes to different vowels [14, 27]. This also implies that formant variations of violin notes may influence our perception of tone quality. Comparing the formants of different violins, we observed that Stradivari violins generally produce higher formants (F1-F4), especially in F1 and F3. These differences are statistically significant, implying that there may be underlying physical differences that distinguish Stradivari violins.

Violin formants F1, F3, and F4 appear to correspond to the dominant vibration modes of the violin, which are the B1 corpus bending mode (including $B1^-$ and $B1^+$), the BH mode, and the bridge-filter mode, respectively [33]. Having higher formant frequencies implies that Stradivari violins can produce higher dominant modes during actual playing, but the underlying relationship between formants and normal modes remains mostly unclear. There is also little understanding of how differences in violin construction or material properties may lead to higher formants, and how higher formants may affect tone perception.

In human voice perception, there is an apparent association between higher formants and brightness, which makes the female voice brighter than the male voice, and front vowels brighter than back vowels [38-39]. It is very interesting to note that Strad violins display greater tendencies to emulate the formants of female front vowels, which is the brightest vowel group. Many concert violinists have subjectively reported that top quality Strad violins are characterized by brilliant tonal qualities. Hence, there may be a correlation between the formant properties of Stradivari violins and their perceived tonal qualities.

We also examined four fine examples of antique Italian violins (Group 3), which are older than the Strads tested but lack Strad-type tonal characteristics (according to concert violinists). Their formants are lower than those of Stradivari violins, and more comparable to modern professional quality violins. This suggests that aging by itself in well-crafted Italian instruments is not sufficient to generate the higher formants of Strad violins. On the other hand, concert violinists also suggest that there are some rare violins not made by Stradivari that possess Strad-like tonal characteristics. When we analyzed such instruments (Group 2), we found that they produce somewhat higher formants than other professional quality violins, and, just like the Strads, they have greater tendencies to emulate the formants of female front vowels. Taken together, the tendency to produce higher formants and to emulate female front vowels appears to correlate better with Strad-like tonal brilliance described by concert violinists than with instrument age.

To conclude, we have demonstrated that there are measurable, objective differences in the resonance properties of Stradivari violins compared to other professional quality violins, both old and new, within the group of instruments selected for this study. It is therefore plausible that the perceived tonal distinction of Stradivari violins frequently described by concert violinists may originate from actual physical differences, not just psychological bias. Having higher formants appears to correlate with the tonal qualities attributed to Stradivari violins, generally described as brilliance. The greater tendency of Strad and DG violins to emulate female front vowels also seems to correlate with their favorable perception by concert violinists. Our work illustrates a novel analytical approach to violin tone by focusing on the spectral envelope of individual notes, rather than the average response curve of the instrument, which can be carried out without special equipment. Further work will be required to extend our new analytical approach to a larger collection of instruments to see if our preliminary observations can be generalized.

V. Acknowledgments

We thank the Chi Mei Museum for lending the valuable violins for the recording session, and Chu-Hsuan Feng for the violin performance. We thank Joseph Nagyvary for recording advice and in-depth discussions, Anders Buen for useful discussions about his published data, Chien-Hung Tu for recording assistance, and David Chiang for manuscript comments.

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