Acoustic evolution of old Italian violins from Amati to Stradivari

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The shape and design of the modern violin are largely influenced by two makers from Cremona, Italy: The instrument was invented by Andrea Amati and then improved by Antonio Stradivari. Although the construction methods of Amati and Stradivari have been carefully examined, the underlying acoustic qualities which contribute to their popularity are little understood. According to Geminiani, a Baroque violinist, the ideal violin tone should "rival the most perfect human voice." To investigate whether Amati and Stradivari violins produce voice-like features, we recorded the scales of 15 antique Italian violins as well as male and female singers. The frequency response curves are similar between the Andrea Amati violin and human singers, up to ∼4.2 kHz. By linear predictive coding analyses, the first two formants of the Amati exhibit vowel-like qualities (F1/F2 = 503/1,583 Hz), mapping to the central region on the vowel diagram. Its third and fourth formants (F3/F4 = 2,602/3,731 Hz) resemble those produced by male singers. Using F1 to F4 values to estimate the corresponding vocal tract length, we observed that antique Italian violins generally resemble basses/baritones, but Stradivari violins are closer to tenors/altos. Furthermore, the vowel qualities of Stradivari violins show reduced backness and height. The unique formant properties displayed by Stradivari violins may represent the acoustic correlate of their distinctive brilliance perceived by musicians. Our data demonstrate that the pioneering designs of Cremonese violins exhibit voice-like qualities in their acoustic output.

Cremona | Brescia | antique violin | formant | timbre

The modern, four-string violin was invented by Andrea Amati (1505–1577) in the early 16th century in Cremona, Italy (1, 2). The complex geometry and structure of Amati violins were rather different from those of preexisting string instruments, setting new standards for both visual and acoustic appeal. Over several centuries, there have been many attempts to modify the basic shape and geometry of violins, such as the guitar violin by Chanot or the trapezoid violin by Savart (3), but all have failed due to negative impacts on the acoustic performance. The basic design of the violin has remained largely unaltered because it is tightly coupled to favorable acoustic properties. However, there is little understanding about the acoustic features that make Andrea Amati's design so appealing in the first place.

After Andrea Amati, the most significant improvement in violin design was brought forth by another Cremonese maker—Antonio Stradivari (1644–1737), who was a pupil of Nicolo Amati, the grandson of Andrea Amati (2, 4). Stradivari, Latinized as "Stradivarius" and abbreviated as "Strad," gradually modified his models and methods through many experiments, and his late-period works (1700–1720) represent the gold standard in violin making. Among the old masters, Stradivari's instruments are the most preferred by modern soloists, and his models are also the most copied by modern makers. Construction differences between Amati and Stradivari violins have been carefully studied, including plate geometry (2, 4, 5), f-hole design (6), varnishing methods (7), and so on. However, the tonal distinctions between Stradivari and Amati violins remain poorly understood.

In our attempt to understand the acoustic evolution of Baroque violins, we were inspired by the writing of Geminiani, a famous violin pedagogue from the Baroque period. He stated, in 1751, that the ideal violin tone should "rival the most perfect human voice" (8). This led us to hypothesize that Andrea Amati's early violins may reproduce some of the acoustic features of human singers.

What voice features could be emulated by the vibration of the violin? In this study, we focus on steady-state features, including frequency response (FR) and the harmonics. Other features, such as transients and noises, are beyond our consideration. The most important spectral feature of human singing is the presence of formants, or specific resonance frequencies, that arise from standing waves in the vocal tract. On average, females have shorter vocal tracts and therefore higher formant frequencies (9, 10). The first four formants (F1 to F4) carry important gender cues when females and males are singing at the same musical pitch (11, 12). In addition, F1 and F2 can be regulated by tongue and mouth shapes, and their changes are associated with vowel discrimination (13, 14).

Bissinger (15) has shown that the violin has four major body/bridge resonance bands in its radiativity profile, in addition to the major air (Helmholtz) resonance mode around 270 Hz. Tai and Chung (16) demonstrated that body/bridge resonance bands lead to voice-like formant features in violin overtones, which can be computed for individual notes using linear predictive coding (LPC) analysis. The first four formants exhibited by violins closely approximate those of human speech reported in the literature (17, 18). Nagyvary (19) demonstrated that the F0, F1, and F2 values of violin notes could be transformed by Pfitzinger's method (20, 21) into vowel backness and vowel height, which compensates for F0 variations. He showed that Guarneri violins exhibit vowel qualities comparable to those of singers. This transformation approach was further validated by Mores (22),

Significance

Amati and Stradivari violins are highly appreciated by musicians and collectors, but the objective understanding of their acoustic qualities is still lacking. By applying speech analysis techniques, we found early Italian violins to emulate the vocal tract resonances of male singers, comparable to basses or baritones. Stradivari pushed these resonance peaks higher to resemble the shorter vocal tract lengths of tenors or altos. Stradivari violins also exhibit vowel qualities that correspond to lower tongue height and backness. These properties may explain the characteristic brilliance of Stradivari violins. The ideal for violin tone in the Baroque era was to imitate the human voice, and we found that Cremonese violins are capable of producing the formant features of human singers.

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who showed that the LPC-predicted vowel qualities of violin notes could be perceptually verified by listeners. These studies have already established the validity of applying LPC formant analysis to violins, but there still lacked direct acoustic comparisons between Amati/Stradivari violins and human singing.

To investigate whether early violins carry certain singing qualities, we recorded the normally played scales of two of the oldest violins in existence: the 1570 Andrea Amati violin and the 1560 Gasparo da Salo violin. Gaspar Bertolotti (commonly called Gasparo da Salo, 1542–1609) was the founder of violin making in Brescia, a city 50 km north of Cremona, and sometimes credited as the coinventor of the modern violin (23). Also recorded were six violins from the Stradivari family and seven additional antique violins from Cremona and Brescia (*SI Appendix*, Table S1). For comparisons, we recorded eight females and eight males who sang eight common English vowels. Using LPC analysis, we observed that instruments made by Andrea Amati and Gasparo da Salo emulate the formant features of male singers. On the other hand, Stradivari violins exhibit higher formants than other antique Italian violins, providing a plausible explanation for their distinctive brilliance.

Results

Violins and Singing Show Similar Frequency Responses. To compare violin notes and human singing, we recorded the one-octave chromatic scale (G#3 to G4, 208 Hz to 392 Hz) for both violins and human singers. To investigate the original design concept of the violin, we derived the FR curves of the 1570 Andrea Amati and the 1560 Gasparo da Salo from the long-term average spectra of the 12 semitones (G#3 to G4). As shown in *SI Appendix*, Fig. S1, the FR curves of these two violins are rather similar to those of male and female singers in the range of 250 Hz to 4,200 Hz. Above 4,200 Hz, the FR of voices is stronger than those of early violins. Despite its common classification as a soprano instrument, violin notes in the lowest fingered octave have weaker high-frequency radiation than human singing.

Spectral Characteristics of Violins and Singing. With both violin recordings and human singing, we conducted LPC analysis using Praat software (24), a popular tool for analyzing speech phonetics. Although originally developed for human speech analysis, Praat appears to work equally well for our violin and singing data for extracting formant peaks from overtone patterns. These formants correspond to resonance peaks in the spectral envelope, which arise from standing waves in the vocal tract in speech and singing (25). Examples of the overtone patterns produced by antique violins and male/female singers are shown in Fig. 1, along with the formant peaks computed by LPC algorithm. Both singers and violins generally exhibit four or five formants below 5,500 Hz, and here we focus only on the first four formants (F1 to F4), which generally appear in the range of 400 Hz to 4,300 Hz. In human speech and singing, formants carry two important perceptual cues. First, F1 and F2 determine vowel quality. This is illustrated in *SI Appendix*, Fig. S2, which demonstrates that the F1–F2 distribution of different sung vowels is generally comparable to those of spoken vowels reported in the literature. Secondly, F1 to F4 are associated with gender differentiation (11, 17, 18): The shorter vocal tracts of females result in higher formant frequencies (10). We were able to compute the F1 to F4 formant frequencies, along with the fundamental frequency F0, for every note played on all antique violins. Therefore, the perceptual significance of violin formants may be investigated from the perspectives of vowel and gender qualities.

Vowel Qualities of the Early Violins. Studies have previously shown that children possess inherent abilities to match violin tones to different vowels (26). Humans produce different vowels mainly by altering F1 and F2 frequencies with different mouth shapes and tongue positions (25). Both F1 and F2 are affected by F0 in human speech and singing, while F3 also plays a minor role in vowel distinction (27, 28). A normalization method to account

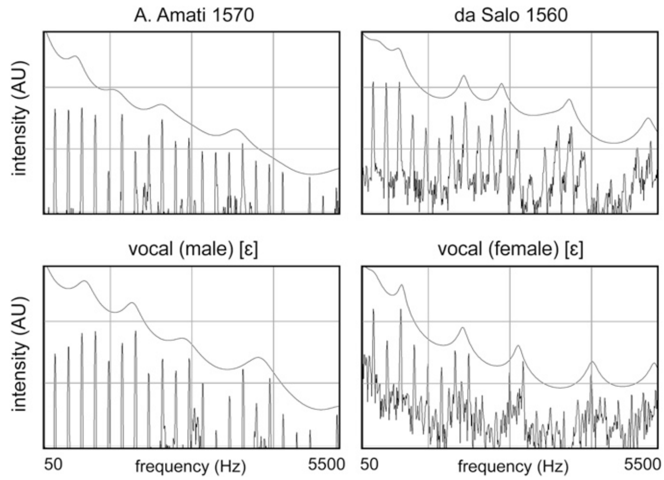

Fig. 1. Formant features of singers and early Italian violins. Sample fast Fourier transform spectra and LPC curves are shown for a recorded B3 note. The word sung was "head," corresponding to IPA vowel [ɛ].

for F0 differences has been proposed by Pfitzinger (21), in which vowel backness and height are calculated from F0, F1, and F2 (see *Supplementary Methods*). The results of such calculations for singers and violins are listed in *SI Appendix*, Tables S2–S4. This method allows each sung word and violin note to be mapped onto an X–Y diagram that resembles the International Phonetic Alphabet (IPA) vowel chart. The individual notes (G#3 to G4) of Amati and da Salo violins are shown in the vowel chart of Fig. 2*A*. This normalization method worked well for all eight common English vowels sung by males and females, and their average positions are plotted in Fig. 2*B*, alongside the mean values of Amati and da Salo violins.

Interestingly, the average vowel positions of Amati and da Salo violins are very close to each other, located in the central region on the IPA vowel chart. This region roughly corresponds to [ɘ], which has central backness and close-mid height. Even though each note on the violin exhibits considerable differences in F1 and F2 values, the spreading pattern still falls within the range of common human vowels (Fig. 2*A*). As such, every violin note appears to carry some degree of human vowel character, and this might have been one of the design goals implemented by Amati and da Salo.

Gender Qualities of the Early Violins. There are six basic voice types, going from higher to lower vocal range: soprano, mezzo-soprano, alto, tenor, baritone, and bass. The first three belong to females, and the latter three belong to males. There is a known correlation between having a higher vocal range and having a shorter vocal tract length (VTL) and therefore higher formants (10, 29). The origin of vocal formants can be explained by standing waves in a half-closed cylinder, and the mathematical relationship between formant frequencies and VTL can be approximated by the following equation (25, 30) (c represents the speed of sound, 343 m/s at 298 K):

$$VTL = (c/4F_1 + 3c/4F_2 + 5c/4F_3 + 7c/4F_4) \div 4 \qquad [1]$$

Using Eq. **1**, we estimated the VTL of male and female singers participating in this study, which turned out to be 16.44 and 15.74 cm, respectively. Compared with the anatomical VTL measurements of different voice types using X-ray images (10), 16.44 cm roughly corresponds to baritones/tenors, while 15.74 cm corresponds to altos/mezzo-sopranos.

The voice types of subjects recruited for this study are restricted by their ability to sing G#3 to G4 comfortably using their natural voices. This vocal range roughly corresponds to tenors or

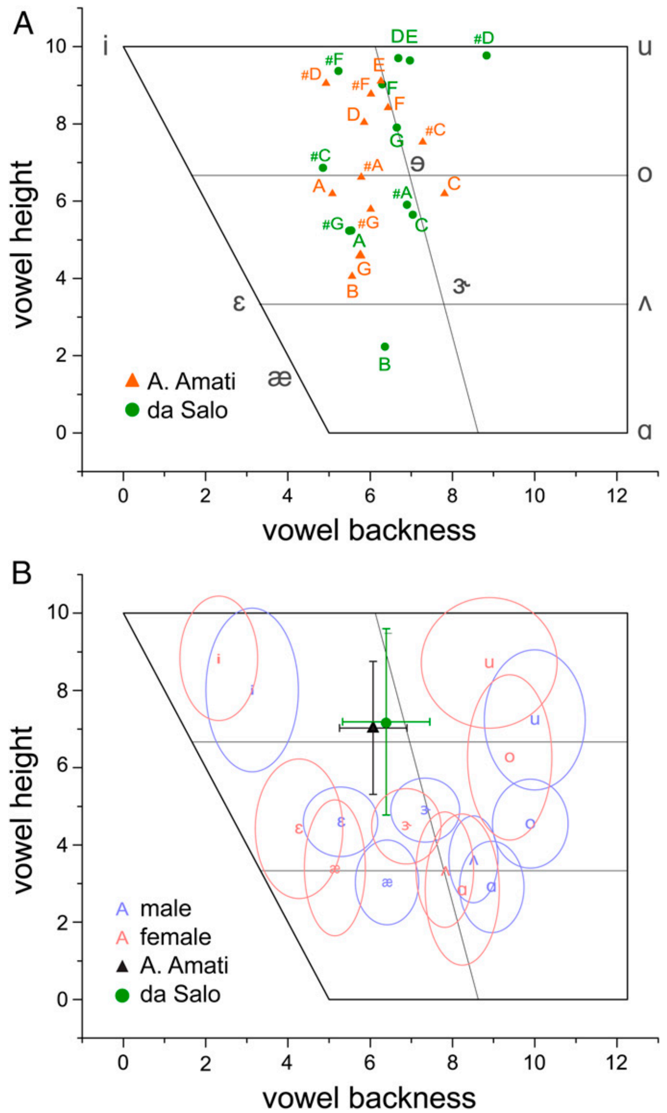

Fig. 2. Vowel qualities of early Italian violins. (*A*) Vowel backness and height of each violin note (G#3 to G4) are mapped onto the IPA vowel diagram. (*B*) For vowels sung by males and females, mean backness and height are represented by the position of the IPA vowel symbol, while the lengths and widths of the ellipses represent SDs. The mean values of violins are represented by colored shapes, and the vertical and horizontal whiskers represent SDs.

baritones for males, and altos or mezzo-sopranos for females (31). This is in good agreement with voice-type categorization based on VTL calculations and corresponding anatomical measurements. As such, Eq. **1** provides a reasonable estimate for the anatomical VTL of singers, and it may also be applied to classify the resonance properties of violins.

Based on LPC analysis, the mean F1 to F4 values of the 1570 Amati violin are 503, 1,583, 2,602, and 3,731 Hz; the 1560 da Salo values are 497, 1,509, 2,525, and 3,594 Hz (Table 1). The F3 and F4 values of both violins resemble those of male singers (*SI Appendix*, Fig. S3). The VTL equivalent calculated for the Amati is 16.71 cm, corresponding to baritones. The VTL equivalent for the da Salo is 17.37 cm, corresponding to basses (10). It therefore appears that early masters in both Cremona and Brescia designed their violins to imitate male voice characteristics. Historical studies suggest that old masters in Cremona and Brescia had close working relationships and codeveloped the modern concept of violins, violas, and cellos (23, 32). The violins of Andrea Amati and da Salo were not only similar in apparent construction and geometry but also in underlying acoustic goals, including formant frequencies.

Strads Produce Higher Formants. Violins made by Antonio Stradivari are widely recognized for their elegant contours and forms, the precision of handwork, and the visual beauty of the varnish. However, it is the superior tone quality that elevates Stradivari to the pinnacle of Italian violin making. The characteristic sound of the Strad violins has been described as "a woody, round, and brilliant tone, full of charm and singing quality" by the Hills, the most prominent violin experts of the 19th century (4).

In his six-decade working career, Antonio had no other apprentices but his two sons, Omobono and Francesco (2, 4). Therefore, there is much interest to understand what acoustic qualities may differentiate the works of the Stradivari family from those of their neighbors in Cremona and Brescia. Our selection of recorded instruments included six instruments from the Stradivari family—five by Antonio and one by Omobono. The non-Strad group included seven instruments from Cremonese masters and two from Brescian masters (*SI Appendix*, Table S1).

Comparing six Strad instruments to nine non-Strad instruments using LPC, the Strad group exhibits higher means for all four formants F1 to F4 (*SI Appendix*, Fig. S4). By two-tailed Welch's t test, the differences in F1, F2, and F3 show P values smaller than 0.01, reaching statistical significance. The formant frequencies of each individual violin are listed in Table 1. The FR curves of Strads and non-Strad violins are rather similar (*SI Appendix*, Fig. S5), with just a few peaks showing significant differences ($P < 0.05$, difference > 3 dB). The Strads have strong formants at 2,766 and 3,141 Hz, as well as strong antiformants around 1,219 and 2,344 Hz. These formants and antiformants may partially account for the higher F2 and F3 of Strad violins, and they have been similarly observed by Buen when comparing Stradivari/"del Gesù" violins to modern violins (33).

Vowel and Gender Qualities of Strads. Compared with non-Strad violins, the F1 and F2 values of Stradivari violins are significantly elevated. When mapped onto the IPA vowel diagram, notes from Strad violins are shifted to the lower left corner, showing increased vowel frontness and openness (Fig. 3). It has been shown that size (magnitude) and brightness are two major attributes associated with phonetic symbolism (34, 35). Increasing

Table 1. Formant frequencies of 15 antique Italian violins

Violin	F1, Hz	F2, Hz	F3, Hz	F4, Hz	VTL, cm
A. Stradivari 1667	537	1,539	2,670	3,745	16.43
A. Stradivari 1707	558	1,654	2,690	3,799	16.54
A. Stradivari 1709	531	1,519	2,702	3,797	15.92
A. Stradivari 1713	538	1,631	2,812	3,814	15.66
A. Stradivari 1722	560	1,496	2,628	3,645	16.52
O. Stradivari 1740	601	1,705	2,660	3,736	15.86
Strad avg.	554	1,591	2,694	3,756	16.15
G. Bertolotti 1560*	497	1,509	2,515	3,594	17.37
A. Amati 1570	503	1,583	2,602	3,731	16.71
P. Maggini 1610	517	1,571	2,649	3,817	16.46
N. Amati 1624	543	1,517	2,617	3,635	16.82
N. Amati 1656	505	1,360	2,582	3,707	17.54
F. Rugeri 1694	482	1,314	2,436	3,681	18.35
G. Guarneri 1706†	492	1,582	2,733	3,774	16.60
C. Bergonzi 1732	532	1,484	2,688	3,750	16.55
B. Guarneri 1733‡	525	1,585	2,559	3,744	16.73
Non-Strad avg.	511	1,500	2,598	3,715	17.02
Male avg.	652	1,440	2,682	3,745	16.44
Female avg.	632	1,571	2,857	4,106	15.74

*Commonly known as Gasparo da Salo.
†Commonly known as Giuseppe Guarneri "filius Andreae."
‡Commonly known as Giuseppe Guarneri "del Gesù."

frontness sounds brighter and smaller (34, 36, 37), while increasing openness or elevating F2 sounds larger (38). Therefore, we may expect Stradivari violins to show greater brightness, but the size effect is less clear. On the F3−F4 diagram, Strad violins are closer to female voices than other old Italian violins (*SI Appendix*, Fig. S6).

The mean VTL of Strad violins is 16.15 cm, as opposed to 17.02 cm for the non-Strad group ($P = 0.006$, Welch's t test). This difference is comparable in magnitude to the difference between female and male singers (16.44 cm vs. 15.74 cm, $P = 0.018$, Welch's t test) (Fig. 4). Compared with the anatomical VTL of singers (10), Strad violins carry the characteristics of tenors/altos, while other old violins are similar to basses/baritones. If we limit the comparison with the three major Cremonese families, then every Stradivari violin ($n = 6$, mean = 16.15 cm) exhibits lower VTL than every Amati/Guarneri violin ($n = 5$, mean =16.88 cm), and the means are significantly different ($P = 0.012$, Welch's t test).

Discussions

The Earliest Violins Exhibit Voice-Like Characters. According to Bissinger (15), the radiativity profile of the violin body has four major resonance bands: global corpus bending modes ($B1^-$ and $B1^+$) around 500 Hz; localized plate vibrations around the bridge and between f-holes (bridge−island modes) at 1,200 and 2,400 Hz; and the bridge rocking mode around 3,200 Hz. This combination of body resonance bands is very similar to the vocal tract formants of the IPA vowel [u] (486, 1,168, 2,307, and 3,359 Hz) in male speech (17).

However, the four resonance bands proposed by Bissinger could not be directly observed in various FR curves published in the literature (33, 39, 40), nor in our FR measurements (*SI Appendix*, Figs. S1 and S5). We previously demonstrated, by LPC analysis, that overtones in individual violins notes do indeed exhibit the four formants that correspond to Bissinger's model (16). The presence of voice-like formants in violin spectra has been further confirmed by the studies of Nagyvary (19) and Mores (22). The physical principle of sound production in human vocalization and violin playing can be similarly explained by the source−filter theory (41, 42), which makes LPC suitable for analyzing the filter properties of both voices (i.e., vocal tract resonances) and violins (i.e., bridge and body resonances).

In this study, we recorded the violins in modern setups, which differ significantly from Baroque setups. In the source part, the string materials, angles, and tensions are different, as well as bow materials and shapes, all of which will affect the overall sound of the violin. In the filter part, which gives rise to formant features, the bass bar has been enlarged and the bridge shape has changed. These changes are known to affect the acoustic output of violins in complex ways (43, 44), but the specific effects on formant frequencies remain to be investigated. Although formant frequencies may be somewhat altered by reverting back to the Baroque setup, the fact that Amati and da Salo violins can produce voice-like formants will most likely still hold true. Moreover, antique Cremonese violins are treasured today over numerous 17th and 18th century violins from other cities and countries mainly because the former sound better in modern setups. Hence, we are more interested in how these violins sound in modern setups as opposed to Baroque setups.

The application of formant analysis to violins and singing becomes less useful as F0 exceeds 400 Hz, because the F0 may exceed F1 for certain vowels, and the widening gap between each harmonic may not coincide with resonance bands. In fact, the intelligibility of sung vowels becomes problematic as singers reach above ∼440 Hz (45, 46). The octave range that ordinary males and females can comfortably sing together coincides with the lowest octave on the violin, around 200 Hz to 400 Hz.

Evolution of Antique Italian Violins. Nia et al. have recently reported that the f-holes gradually lengthened going from Amati to Stradivari violin models. Based on computer simulation, they predicted the air resonance mode of Stradivari violins to carry higher frequency and greater power (6). Our data demonstrate that Strad violins also produce higher F1 to F4 formants than

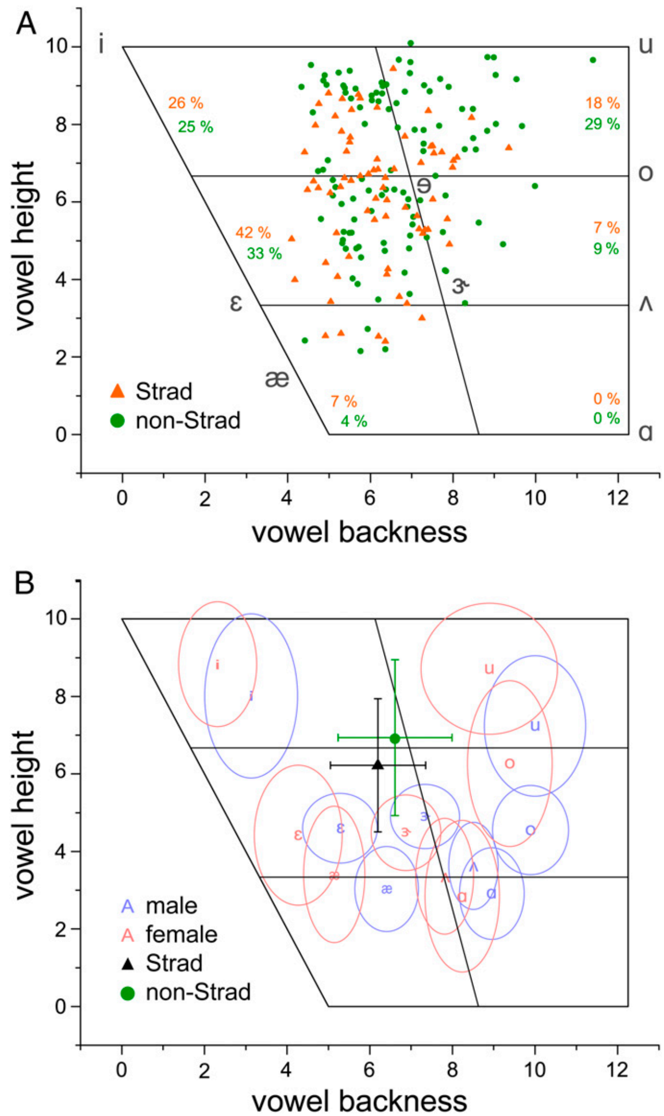

Fig. 3. Vowel quality comparisons between Strad and non-Strad violins. (*A*) Vowel backness and height of individual violin notes (six Strads and nine non-Strads, 12 pitches) are mapped onto the IPA vowel diagram. The diagram is divided into six regions, labeled with percent distributions. (*B*) For vowels sung by males and females, mean backness and height are represented by the position of the IPA vowel symbol, while the lengths and widths of the ellipses represent SDs. The means of Strad and non-Strad groups are represented by colored shapes, with the vertical and horizontal whiskers representing SDs. P values for mean comparisons are 0.036 for backness and 0.009 for height, by two-tailed Welch's t test ($n = 72$ for Strad; $n = 108$ for non-Strads).

other old Italian violins. How Stradivari managed to raise F1 to F4 remains unclear, although it is generally stated that he reduced plate arching relative to Amati and Stainer, resulting in brighter tones and greater power (4, 5). Stradivari also experimented with the outer contour of plates, but it may be less relevant acoustically (47). The varnish structure of Stradivari violins is more complex than those of Amatis (7, 48), which may exert certain tonal effects (4, 5, 40). Moreover, Stradivari treated his maple chemically before making the instruments (49–51), but it is unclear if the Amatis did the same or if instrument acoustics was affected.

The acoustic quality that differentiates Stradivari violins from other old Italian violins is often described by experts as "brightness" or "brilliance" (4, 52). Our data suggest two plausible explanations for such distinctions: (i) Strads produce higher

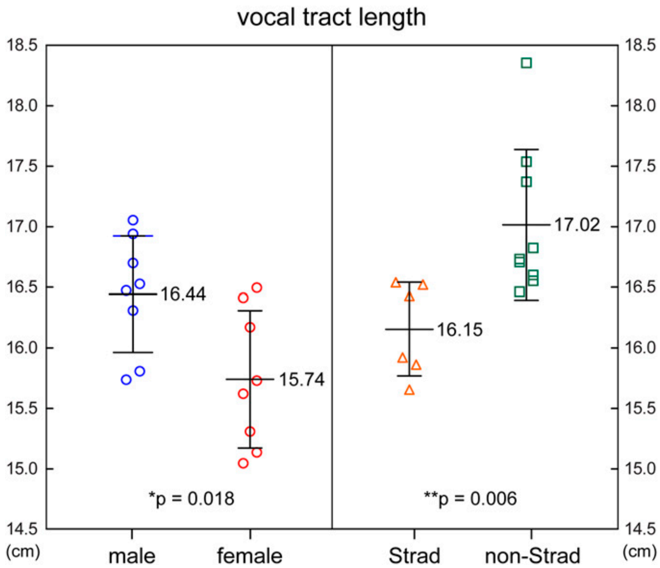

Fig. 4. VTL estimates for male vs. female singers, and Strad vs. non-Strad violins. Open colored shapes represent individual data points, the center band represents the mean, and the whiskers represent SDs. *P* values below 0.05 and 0.01 (by two-tailed Welch's *t* test) are indicated by * and **, respectively. For male, female, Strad, and non-Strad groups, n = 8, 8, 6, and 9, respectively.

F1 to F4 frequencies, which place them closer to female voices; and (*ii*) on the vowel diagram, Stradivari violins show greater frontness, which is associated with increased brightness (34, 36, 37). Elevated formants may therefore be the acoustic correlate for the characteristic brilliance of Stradivari violins, but additional perceptual experiments are required to validate this hypothesis.

Two previous studies have reported that Stradivari violins exhibit higher formants and more vowel "frontness" than other old Italian violins (16, 22), but both compared violin notes to preexisting speech datasets without recording human singing. Males generally speak with F0 around 120 Hz, which is unplayable on the violin, while females speak around 220 Hz (17). Hence, it was difficult to compare violin formants to speech data due to F0 mismatching. The interviolin-group differences observed in our previous study (16) are similar to the results of this study, although the previous recording session failed to cover every semitone in the octave and only recorded from two microphone positions. In contrast, the current recording session covered all 12 semitones, with six microphone positions. Despite such differences, the unique formant properties of Strad violins appear to be robustly detectable under different experimental conditions, and this study offers insights regarding how they relate to the qualities of human singing voices.

The average vowel position of Stradivari violins on the IPA diagram does not coincide with the eight English vowels recorded in this study. Instead, it resembles nasalized, open-mid, front vowels corresponding to French words *vin* [ɛ̃] or *peu* [ø], sung by opera singers, as reported by Nagyvary (19). However, we did not further investigate the issue of vowel nasalization or why some violins sound more nasal than others.

Judging from our data, it appeared that Italian violins made before Stradivari's prime generally exhibited male vocal characters. It has been recorded, in 1674, that the Italian violinist Nicholas Matteis "had a stroak so sweete, and made it speak like the voice of a man" (53). Matteis probably did not play an instrument by Stradivari, who was relatively unknown at that time. When Andrea Amati and Gasparo da Salo invented the modern violin, most of the singers giving public performances were males. Famous female singers began to appear on stage in the early 1600s (54), and gained great popularity by the end of Stradivari's career (55). Therefore, the acoustic evolution from Amati to Stradivari, gradually gaining more feminine character, coincided with the rising popularity of professional female singers. This evolutionary trend is consistent with the Baroque-era concept that the tone of the violin should "rival the most perfect human voice" (8).

Objective vs. Subjective Assessment. Among concert violinists and instrument collectors, there has been a strong consensus over the past two centuries that violins with superlative timbre were mostly built by Antonio Stradivari and Guarneri del Gesù. Scientifically, timbre is defined as the character or quality of a musical sound distinct from its loudness, pitch, duration, and spaciousness (56, 57). Although numerous studies have attempted to investigate the timbre quality of Stradivari violins, their findings have been largely contradictory.

There are still ~500 Stradivari violins in existence (2, 4), but many have suffered severe wear and tear, and most have been extensively modified and repaired. Some experts estimate that only one-fifth of them still qualify as soloist instruments. Due to their extraordinary value and rarity, it is very difficult to gather a group of top-quality Strads for research, especially when there is a lack of objective standards to assess their timbre quality for prescreening. The loan periods of valuable instruments for research are often short, preventing setup optimization and player adaptation to exhibit their full potentials.

Several studies have reported differences in the FR curves of Stradivari against other violin groups (33, 39, 40, 58), but no consensus was found, probably due to different measurement methods and cohort selection. In our FR data (*SI Appendix*, Fig. S5), non-Strad violins exhibit a strong formant around 2,344 Hz, similar to the center frequency of the singer's formant reported for basses (29, 59). In comparison, Stradivari violins show strong formants around 2,776 and 3,141 Hz, which corresponds to the singers' formant of tenors and female singers (altos and sopranos), respectively.

Recently, Fritz et al. (60–62) conducted the subjective assessment of old Italian violins under blind conditions, reporting that players and listeners failed to identify favorable timbre qualities in Strad violins over modern master violins. However, there were two fundamental drawbacks in their experimental design. First, working memory for timbre only lasts from a few seconds to tens of seconds in humans (63–65), shorter than the time interval required for the player to switch instruments and play the same passage. The timbre memory of the previous instrument may have already decayed when the next violin is being played (66). Secondly, Fritz et al. did not measure or report the loudness of individual instruments, meaning that subjective evaluations about timbre and preference could have been confounded by differences in loudness. Even if loudness were measured, there would have been no simple method to normalize for interinstrument differences during live listening tests. Louder violin tones usually sound fuller and more preferable in side-by-side comparisons (67). Hence, without loudness equalization, it would be difficult to properly assess timbre. In the objective analyses of recorded violins, either loudness can be normalized (e.g., in FR comparisons) or loudness-independent tests can be used (e.g., LPC analysis) to investigate timbre differences.

It is widely recognized that we have recently entered a second golden age of violin making, two and a half centuries after the first golden age in Cremona (1550–1750). Violin making standards are extremely high today and continue to rise. This study makes no attempt to judge the relative merits of Strad violins against modern violins, which is a very diverse group that defies simple categorization. Instead, we focused on antique Italian violins from Cremona and Brescia, tracing their acoustic evolution from the perspective of voice-like characters.

To imitate the filter properties of the human voice, especially the female voice, is a novel concept in acoustic tuning for modern violin making. However, it is also a historical concept already noted by Baroque writers (8, 53), one likely to be adopted by old master makers who lacked access to modern acoustics knowledge and measurement tools. Pushing violin formants even higher to mimic mezzo-soprano or soprano voice types, beyond what Stradivari has achieved, could be a new challenge for 21st century violin makers. Additional research is required to understand the physical and material factors that influence formant properties in violins, and how voice-like formants are perceived by listeners. It remains to be explored whether this design concept is also applicable to violas and cellos, or even other string instruments across different cultures.

Materials and Methods

We recorded the scales of 15 old Italian violins (*SI Appendix*, Table S1) at Chimei Museum (Tainan, Taiwan), playing the chromatic scale (G#3 to G4). We also recorded the singing of eight males and eight females over the same scale. They sang these eight words: "had, head, heard, heed, hod, hoed, hud, who'd," which correspond to IPA symbols æ, ɛ, ɝ, i, ɑ, o, ʌ, and u, respectively. All human subjects gave informed consent and their participation was approved by the National Taiwan University Research Ethics Committee. Please refer to *SI Appendix* for further details on sound recordings and analyses.

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